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Optimal Dispatch of Green Hydrogen Production

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**Optimal Dispatch of Green
Hydrogen Production**

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Abstract

This project proposes a hybrid system for hydrogen production, which includes a connection to the grid, a source of renewable energies, namely photovoltaic (PV), a Battery Energy Storage System (BESS), and a PEM (Proton Exchange Membrane) electrolyzer modelled from commercial technologies available. A dispatch optimization algorithm will evaluate the price of the energy inputs and the power available from the solar PV system and will decide the operation on an hourly basis to maximize net profit in a year timeframe. This algorithm will have a daily hydrogen production constraint.

When the price of electricity is low, the energy is used for two purposes. First, to electrolyze water in the electrolyzer system and second, to store it in the BESS. The stored energy will be used to produce hydrogen when electricity prices are high or inject back to the grid when it is economically sound to do. The PV input will be used to alleviate the need for energy from the grid, therefore, it can be used to feed the electrolyzer or to store in the batteries or to inject back to the grid. In this study, a multi-energy system is modelled and its operation strategy for green hydrogen production is analyzed.

Four topological scenarios were chosen, which include Scenario 1 (Grid + PEM), Scenario 2 (Scenario 1 + BESS), Scenario 3 (Scenario 2 + Grid injection), and Scenario 4 (Scenario 3 + Solar PV). These scenarios facilitate a comprehensive assessment of the system's economic and environmental performance contingent on the installed assets.

In addition to the scenario analysis, the study broadens its scope by exploring two diverse geographical regions, Sweden and Spain, as case studies. This comparative approach offers invaluable insights into the role of factors like lower electricity prices and reduced solar energy availability, as observed in the Swedish case, versus the dynamics of higher electricity prices and abundant solar energy in the Spanish context.

Lastly, the research undertakes a thorough sensitivity analysis, considering two pivotal factors with great influence over the system's behavior: hydrogen pricing and BESS capacity. This exploration enriches our understanding of how variations in these factors can impact the system's operational and economic viability.

Keywords: Green Hydrogen, Dispatch Optimization, Multi-Energy System, Energy Storage, LCOH.

Sammanfattning

Detta arbete presenterar ett hybridsystem för produktion av vätgas som integrerar elnätsanslutning, förnybar energiförsörjning genom solceller (PV), ett batterilagret (BESS) och en PEM-elektrolysör.

För detta energisystem har en optimeringsalgoritm för systemdrift skapats. Denna algoritm utvärderar energipriser och tillgänglig kapacitet från PV-systemet, och drifftar systemet på timbasis för att optimera nettovinsten över ett år, med dagliga produktionsgränser för vätgas.

När elpriset är lågt används energin för två ändamål: Att elektrolysera vatten i elektrolyssystemet, och att lagra det i batterilagret (BESS). Den lagrade energin från BESS kommer att användas för att producera vätgas när elpriserna är höga eller för att injicera tillbaka i elnätet när det är ekonomiskt försvarbart. Energin från PV-systemet används för att lindra behovet av energi från elnätet och kan användas för att driva elektrolysören, eller för att lagra i batterierna, eller för att injicera tillbaka i elnätet. I denna studie modelleras en elektrolysör, baserat på kommersiellt tillgängliga teknologier, och en driftsstrategi utvecklas för produktionen av grön vätgas.

Fyra unika scenarier valdes ut: Scenario 1 (Nät + PEM), Scenario 2 (Scenario 1 + BESS), Scenario 3 (Scenario 2 + Injektion till Elnät) och Scenario 4 (Scenario 3 + Solenergi från PV). Dessa scenarier underlättar en omfattande bedömning av systemets ekonomiska och miljömässiga prestanda beroende på installerade tillgångar.

Utöver scenarioanalysen vidgar studien sin omfattning genom att utforska två olika geografiska regioner, Sverige och Spanien, som fallstudier. Denna jämförelse ger värdefulla insikter i systemfaktorernas roll, där det Svenska fallet (med lägre elpriser och minskad tillgänglighet av solenergi) ställs emot the Spanska fallet (med högre elpriser och rikligt med solenergi).

Slutligen genomför forskningen en noggrann känslighetsanalys och beaktar två avgörande faktorer med stor påverkan över systemets beteende: Priset på såld vätgas och BESS-kapaciteten. Denna utforskning berikar vår förståelse för hur variationer i dessa faktorer kan påverka systemets operativa och ekonomiska livskraft.

Nyckelord: Grön vätgas, UppdragsOptimering, Multi-EnergiSystem, Energilagring, LCOH.

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Nomenclature

AC	Alternating Current	KPI	Key Performance Indicator
ALK	Alkaline Fuel Cell Technology	LCOH	Levelized Cost of Hydrogen
AWE	Alkaline Water Electrolysis	Li-Ion	Lithium Ion
AMs	Analytical Methods	LiB	Lithium Battery
ANN	Artificial Neural Networks	LP	Linear Programming
BESS	Battery Energy Storage System	LFP	Lithium Ferro-Phostate
BOP	Balance of Plan	Max	Maximum
CAPEX	Capital Expenditure	MEA	Membrane Electrode Assembly
CCP	Chance Constraint Programming	MhAs	Meta-Heuristic Algorithms
CO₂	Carbon Dioxide	MILP	Mixed Integer Liner Programming
DC	Direct Current	MINLP	Mixed Integer Non-Linear Programming
DP	Dynamic Programming	MOs	Mathematical Optimizations
ENTSO-E	European Network of Transmission System Operators for Electricity	NMC	Lithium-Nickel-Manganese-Cobalt-Oxide
ESS	Energy Storage System	NPV	Net Present Value
EU	European Union	OPEX	Operational Expenditure
ETS	Emissions Trading Scheme	O&M	Operation & Maintenance
FCEV	Fuel Cell Electric Vehicle	PEM	Proton Exchange Membrane
FF	Firefly Algorithm	PMs	Probabilistic Methods
GA	Genetic Algorithm	PPA	Power Purchase Agreement
GAMS	General Algebraic Modelling System	PV	Photovoltaic
GHG	Greenhouse Gases	SEC	Specific Energy Consumption
H₂	Hydrogen	SMR	Steam Methane Reforming
HMs	Hybrid Methods	SOC	State of Charge
IEA	International Energy Agency	SOEC	Solid Oxide Electrolyzer Cell
IPA	Internal Point Algorithm	TSOs	Transmission System Operator
KOH	Potassium Hydroxide	WACC	Weighted Average Cost of Capital

Units

Acm⁻²	Ampere per square centimeter
bar	Bar
CO_{2eq}	CO ₂ equivalent
EUR	Euros
kg	Kilograms
kh	Kilohours
kWh	Kilowatt-hour
MWh	Megawatt-hour
m³	Cubic meters
min	Minutes
MPa	Megapascal
MWp	Megawatt peak
Nm⁻³	Newton per cubic meter
°C	Temperature in Celsius
USD	US Dollars
V	Volts
W_{ac}	Watts in AC
W_{ac-year}	Watts in AC a year
W_{dc}	Watts in DC
W_{dc-year}	Watts in DC a year
Wh	Watt-hour
Wh-year	Watt-hour a year

1 Introduction

With an increasing consumption of fossil fuels and environmental problems, decarbonizing the power sector has turned into an essential task for Governments and individuals. Figure 1 shows the renewable energy in total final energy consumption in 2019 (REN21, 2022). From this chart it is possible to identify that the large penetration of renewables in recent years in the heating and cooling, transport and power sectors is still far from fully decarbonizing energy systems. Moreover, even with a generation matrix consisting 100% on renewables sources, further efforts would be needed to decarbonize the heating and cooling and transport sectors.

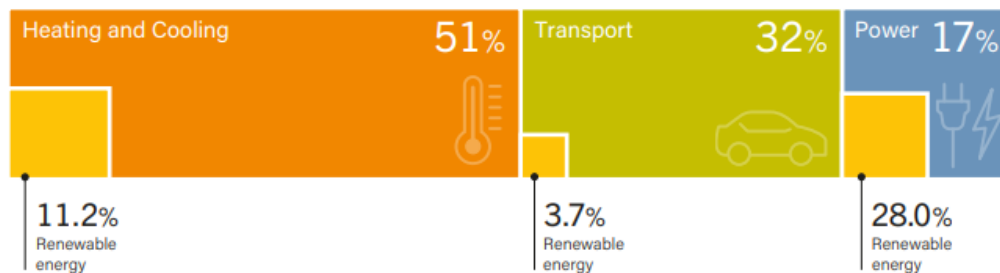


Figure 1. Renewable Energy in Total Final Energy Consumption, by Final Energy Use, 2019 (REN21, 2022)

Figure 2 illustrates the evolution of the power sector between 2011 and 2021. The share of renewable energies in this sector has increased approximately 8 percentage points in one decade. The increasing trend is largely due to the deployment of solar and wind power and the decreasing use of fossil-fueled technologies, however, the goal to be no longer dependent on the latter to keep energy systems running is not yet a feasible scenario in the short term.

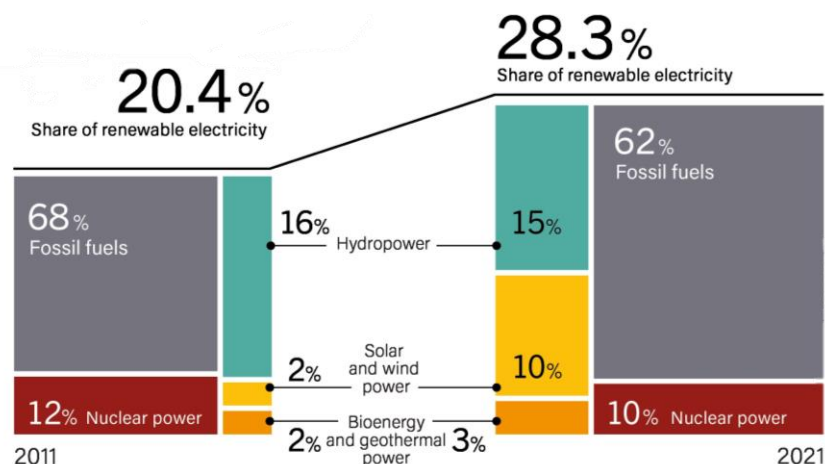


Figure 2. Share of Renewable Energy in Electricity Generation, 2011 and 2021 (REN21, 2022)

According to the (IEA, 2019), hydrogen holds significant potential for a clean, secure, and affordable energy future. The report emphasizes that hydrogen plays a central role in decarbonizing challenging sectors like long-haul

transport, chemicals, and iron and steel production. The (Green Energy Transitions, 2021) estimates that investments in the hydrogen value chain could reach approximately \$15 trillion by 2050, with a peak of around \$800 billion annually in the late 2030s. Consequently, substantial efforts are required in the energy sector to establish a hydrogen economy.

However, there are several limitations associated with the development of this economy, as highlighted by the (IEA, 2019). Currently, the cost of producing green hydrogen from renewable electricity is higher compared to hydrogen produced from fossil fuels. This increased cost is primarily due to the ongoing maturation process of fuel cells, refueling equipment, and electrolyzers. Among these, electrolyzers contribute significantly to the expense of renewable hydrogen production, along with the price of electricity.

Another challenge lies in the fact that most of the hydrogen produced today is derived from fossil fuels, resulting in carbon dioxide emissions that undermine its potential as a climate change solution. To address this issue, carbon capture and storage techniques can be employed to mitigate emissions and transform hydrogen into a sustainable energy source.

To effectively promote the establishment of a hydrogen economy, collaboration between policymakers and industries is crucial. Both parties must work together to develop appropriate regulations that address investment barriers and create a level playing field for developers, thereby facilitating the transition from feasibility studies to tangible projects.

The primary focus of industry and research has been on reducing capital expenditures (CAPEX) and scaling up electrolysis plants to lower manufacturing costs, thus the levelized cost of hydrogen (LCOH) (Matute *et al.*, 2022). However, the annualized costs of these projects also arise from electricity consumption, therefore, the objective of this thesis is to study the economic feasibility of these large-scale projects when integrated with steerable assets that can alleviate the costs of the electricity and reduce the cost of operation of hydrogen production plants. Study cases are designed to identify the effect on energy prices and solar availability when assessing these projects.

2 Background and Literature Review

This section provides an overview of the background and literature review relevant to the optimal dispatch of green hydrogen production. It highlights the significance of dispatch in modern energy systems and explores the role of hydrogen as an influential energy carrier on a global scale. The subsections in this section delve into various subsystems involved in green hydrogen production, including the renewable energy input (such as photovoltaic or solar energy), the incorporation of battery energy storage systems to enhance operational flexibility, different electrolyzer technologies with their underlying operational principles, and the comprehensive consideration of all components involved in the hydrogen process through the Balance of Plant (BOP) concept. Furthermore, the section presents a literature review encompassing diverse optimization algorithms and their applications in related areas like energy asset sizing and location. It also addresses the frameworks utilized in different studies to define these optimization algorithms.

2.1 Energy Dispatch

To drive the hydrogen economy forward, both researchers and industries have been primarily dedicated to scaling up electrolyzer production to curtail project capital expenditures (CAPEX) and stimulate increased interest from investors and project developers. In a study by (Nguyen et al., 2019), experts within the hydrogen sector were interviewed, and they foresee substantial investments in electrolyzer technologies, enhanced production techniques, and standardized products. Similarly, (Saba *et al.*, 2018) conducted a study on the development of water electrolysis, projecting a continued and significant growth in investment in this technology up to 2030. These studies demonstrate the predominant focus on reducing CAPEX, rather than emphasizing the operational aspects of electrolyzer technology.

To enhance the performance of hydrogen-based projects, it is crucial to delve into the operation and dispatch of power plants. Dispatch in this context refers to the resource planning conducted by the plant's operator, which involves making decisions on resource allocation and utilization. It serves as a vital tool for maximizing economic profitability by optimizing the operational schedule and resource utilization, taking into account variable costs, anticipated energy market prices and operational constraints of the technologies involved such as ramp up, maximum and minimum operational values, among others.

Matute, Yusta and Correas developed a model utilizing a multi-megawatt electrolysis system to meet hydrogen demand in Spain's mobility sector while also providing secondary regulation services for grid support (Matute, Yusta and Correas, 2019). The study illustrates how the hydrogen economy can benefit from various revenue streams within existing energy systems, and the combination of different technologies can reduce operational costs in green hydrogen production.

Nguyen et al. conducted a techno-economic analysis on a large-scale electrolytic hydrogen production plant, examining the impact of pricing schemes in Canada, California, and Germany (Nguyen *et al.*, 2019). The results indicate that by avoiding operation during peak hours, electricity costs can be reduced by up to 30% in Ontario and California wholesale markets.

The study conducted by (Matute *et al.*, 2022) concludes that optimal dispatch is crucial for supporting hydrogen production while considering project income and sustainability indicators, particularly by prioritizing hydrogen production when renewable energy sources are available. On a smaller scale, (Şevik, 2022) simulated a PV-trigeneration-hydrogen production hybrid system with a capacity of hundreds of kilowatts. The implementation of optimal dispatch yielded positive outcomes, ensuring reliable electricity supply and minimizing the need for hydrogen storage.

By focusing on the operation and dispatch of green hydrogen facilities, several benefits emerge. These include participation in flexibility markets to stabilize the grid, the energy storage potential of hydrogen, reduced electricity costs, and the ability to minimize CO₂ emissions as an optimization objective, among others. The motivation of this paper is to explore the operation of hybrid systems, unlock the potential of individual controllable assets, and ensure the development of a green, secure, reliable, and economically feasible project.

2.2 Hydrogen as a Carrier

Hydrogen offers unique advantages as an energy carrier. The combination of electricity and water results in hydrogen and its conversion into heat or power is a simple and environmentally friendly process. When hydrogen is burned with oxygen to produce water, there are no emissions of pollutants. This process is supported by (NASA, 2003), where astronauts utilize this technology for generating drinking water aboard the space shuttle. Despite being the most abundant element on Earth, hydrogen does not exist naturally in its pure form. (Bossel and Eliasson, 2003) highlights that it must be separated from chemical compounds, achieved through either water electrolysis or chemical processes using hydrocarbons or other hydrogen carriers. The electricity required for electrolysis can eventually be sourced from clean renewable energy, such as solar radiation, wind and water kinetic energy. As long as the energy used to produce hydrogen is sustainable, hydrogen can be considered a truly green fuel.

Various methods exist for hydrogen production due to its energy input requirements. (Conte *et al.*, 2009) provides a summary of different technologies, presented in Figure 3. The figure distinguishes between fossil fuels and renewables as energy sources, while also differentiating applications in the transport sector's fuelling stations or centralized electricity generation. Moreover, it identifies processes integrated with CO₂ sequestration (also known as carbon capture and storage processes) for significant environmental impact reduction.

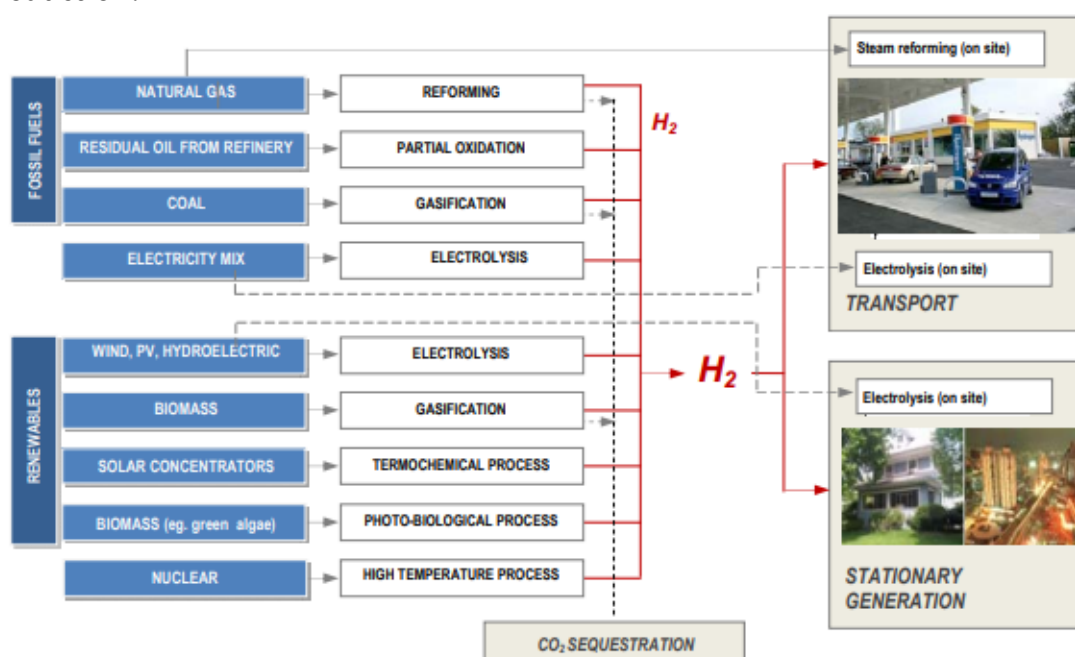


Figure 3. Summary of different technologies for hydrogen production (Conte *et al.*, 2009)

Common hydrogen production processes today involve Steam Methane Reforming (SMR) using methane or electrolysis powered by electricity. Once you have hydrogen, it can be burned directly or mixed with oxygen in a fuel cell.

The reaction in the fuel cell produces electricity and heat, with water as the sole byproduct.

In a fuel cell, gases are stored externally to the cell and electrical energy is generated at the electrode/electrolyte interface. listed a large range of fuel cell types in Table 1 (Zamel and Groos, 2022). These cells function similarly to batteries, comprising an anode, cathode, and electrolyte. Leading the hydrogen transition are Polymer Electrolyte Membrane (PEM) and Alkaline (ALK) technologies, with PEM offering versatility for various applications and ALK balancing high efficiency with lower component costs, addressing key challenges in hydrogen economy development. Subsequent subchapters will explore these technologies further in the context of electrolyzers.

Fuel Cell Type	Electrolyte	Application Fields	Advantages	Disadvantages
Polymer Electrolyte Membrane	Perfluorosulfonic acid	backup power, portable power, distributed generation and transportation	solid electrolyte reduces corrosion and electrolyte management problems, low temperature and quick startup	expensive catalysts, sensitive to fuel impurities, low temperature waste heat
Alkaline	aqueous solution of potassium hydroxide soaked in a matrix	military, space	fast cathode reaction leads to high performance, low cost components	sensitive to CO ₂ in fuel and air, electrolyte management issues
Phosphoric Acid	phosphoric acid soaked in a matrix	distributed generation	higher temperature enables combined heat and power, increased tolerance to fuel impurities	Pt catalyst, long startup time, low current and power
Molten Carbonate	solution of lithium, sodium and/or potassium carbonates, soaked in a matrix	electric utility, distributed generation	high efficiency, fuel flexibility, catalyst flexibility, suitable for combined heat and power	high temperature
Solid Oxide	Yttria stabilized zirconia	auxiliary power, electric utility, distributed generation	high efficiency, fuel flexibility, catalyst flexibility, solid electrolyte, suitable for combined heat and power and CHHP, hybrid/GT cycle	high temperature corrosion and breakdown of cell components, high temperature operation requires long startup time and limits

Table 1. Fuel cell by type, its electrolyte, applications, advantages and disadvantages (Zamel and Groos, 2022)

For the industrial sector, steel and cement industries are particularly interested in adopting hydrogen to address their hard-to-abate processes involving high temperatures and reliance on coal, leading to high carbon emissions. (Tautorat *et al.*, 2023) notes hydrogen-based production as a prominent topic, with

concerns focusing on infrastructure needs for hydrogen production, import, transport, and storage.

Bolt, Dincer and Agelin-Chaab propose a multigeneration system integrating hydrogen production to meet the energy demands of cement plants, yielding promising results (Bolt, Dincer and Agelin-Chaab, 2023). This can be contrasted with the current Swedish iron and steel industry, where, as explained by (Öhman, Karakaya and Urban, 2022), the industry is innovative and distinguished by its climate-conscious approach. Sweden took the initiative to adopt green hydrogen-based direct reduction ahead of other European steel companies. Sweden benefits from abundant low carbon electricity from hydropower and nuclear sources, providing cost advantages for industrial users. Additionally, the country boasts a strong and supportive energy and climate policy, aiming to achieve net zero emissions in the Swedish economy by 2045.

Another niche exists in commercial transport, especially for heavy vehicles that fall outside the capacity of batteries. The weight of such vehicles can compromise their payload capacity, rendering them non-competitive. Hydrogen fuel cell heavy-duty trucks offer faster refuelling, greater cargo capacity, and extended range compared to battery-powered alternatives. (Camacho, Jurburg and Tanco, 2022) show that there is a 270% growth in published papers between 2019 and 2021 on Fuel Cell Electric Vehicles (FCEV). The surge in publications reflects the industry and researcher's commitment to decarbonizing the transport sector, covering various topics such as public policies, hydrogen supply chain, environmental impact, drivetrain technology, fuel cell applications and storage tank applications.

This increase in research indicates society's value on environmentally friendly solutions, consequently increasing their willingness to pay for GHG emissions reduction-aligned technologies, as evidenced in (Yan and Zhao, 2022) study conducted in China. Results show that the willingness to pay for hydrogen fuel cell heavy-duty trucks over diesel heavy trucks is 50% more. Moreover, it can be interpreted as an indicator for manufacturers to firmly believe the end user is willing to pay more for clean technologies.

Regarding hydrogen transport, (Hydrogen Europe, 2021) states that transporting hydrogen through pipelines over distances of a few thousand kilometers proves to be a highly economical method for energy transportation. When compared to electricity transport across similar distances, hydrogen transport is approximately ten times more cost-effective. Consequently, new initiatives to develop the needed transportation infrastructure are being developed. (Gas for Climate: A path to 2050, 2022) aims to create a comprehensive pipeline covering 25 EU Member States plus Norway, the United Kingdom, and Switzerland, envisioning a total pipeline network of nearly 53,000 kms by 2040, comprising around 60% repurposed existing infrastructure and 40% newly constructed hydrogen pipelines.

Hydrogen production is rapidly becoming more energy efficient and cheaper, driven primarily by technological advances. Government support in decarbonization efforts fosters a conducive ecosystem for a new hydrogen economy. According to a report by (McKinsey Insights, 2022), there is an estimated investment gap of 460 billion US dollars until 2030. Hydrogen's pivotal role in the long-term pathway to achieving net-zero emissions is set to revolutionize numerous sectors.

2.3 Subsystems

Given the considerable potential of hydrogen as a key enabler in decarbonizing the economy, extensive research and studies have been conducted on hydrogen energy systems and the various energy and revenue streams associated with them.

A thorough literature review was performed to explore the components of multi-energy hydrogen systems, aiming to understand how these projects are conceptualized and which key elements facilitate their implementation. It is worth noting that these projects heavily depend on their specific execution context, leading to a lack of standardized solutions. Factors such as available energy sources, storage capacity, grid connectivity, or self-consumption systems all play a vital role in shaping the system design.

The literature review identified the diverse energy sources utilized, storage capacities, system topologies, optimization methods under study, and the primary focus of each paper. The classification was predominantly based on the review table presented in (Gallardo et al., 2022). Furthermore, the optimization methods were categorized following the metric provided by (Yang *et al.*, 2020)

AUTHOR	Energy Source								Storage		Grid	
	PV	Wind	Hydro	SC	Biogas	SMR	GT	Diesel Gen	Battery	H2	On	Off
(Liaqat, Rehman and Ahmad, 2020)	X								X			X
(Ji et al., 2023)		X	X		X				X	X		X
(Gallardo et al., 2022)	X											X
(Schnuelle et al., 2020)	X	X									X	
(Rezaei, Khalilpour and Mohamed, 2021)		X									X	
(Mohammadshahi et al., 2022)	X								X	X	X	
(Yang, Zhang and Lin, 2015)	X			X						X		X
(Zghaibeh et al., 2022)	X									X		X

(Şevik, 2022)	X			X	X		X	X
(Vo et al., 2022)				X			X	X
(Gao et al., 2022)	X	X						X
(Marocco et al., 2021)	X					X	X	X
(Wang et al., 2022)	X				X		X	X
(Mehrenjani et al., 2022)		X	X				X	X
(Matute et al., 2022)	X							X
(Phan-Van, Takano and Nguyen Duc, 2023)	X					X	X	X
(Wang and Zhang, 2023)		X					X	X
(Lu, Li and Li, 2023)	X						X	X
(HassanzadehFard et al., 2020)	X	X		X			X	X
(Zhang et al., 2022)	X	X				X		X
(Hong, Wei and Han, 2022)		X					X	X
(Grüger et al., 2019)		X					X	X
(Kilic and Altun, 2023)	X	X			X		X	X
(Zhang et al., 2023)	X	X	X				X	X

Table 2. Review on similar hydrogen-based energy systems, organized by energy sources, storage system and topology

Table 2 presents a literature review focusing on green hydrogen production for the background section. While some papers explored hydrogen storage, this research primarily concentrates on the dispatch and operation of hydrogen production plants at an hourly basis, considering variables such as electricity price, renewable energy production, and electrolyzer operation. Investigating the impact of hydrogen storage provides limited value as its implicit timeframe exceeds that of the rest of the system. Moreover, since this study emphasizes hydrogen's significance as a commodity for creating products like green ammonia or green methanol, fuel cells were excluded from the analysis. The production plant's main priority is meeting hydrogen demand, rendering the timescale for hydrogen storage consideration irrelevant to optimal dispatch. The assumption in this case is the availability of a hydrogen storage buffer with sufficient capacity to handle a 3-day demand.

On the other hand, the effect of batteries can influence and impact the dynamic behavior of the production plant; thus, a battery system is included in the study. The relevance of battery storage and its positive implications on the project's operation are supported by studies conducted by (Liaqat, Rehman and Ahmad, 2020; Marocco *et al.*, 2021; Mohammadshahi *et al.*, 2022; Phan-Van, Takano and Nguyen Duc, 2023).

Among the 24 documents, 13 considered grid-connected systems, while 10 were off-grid, requiring the hybrid between renewable sources and the electrolyzer to fully meet hydrogen demand. (Zhang *et al.*, 2022) conducted a comparison and analysis of both configurations, revealing better economic outcomes for the grid-connected case. Considering the objective of promoting economically viable hydrogen-based projects in this thesis, the decision is to favor a connection to the grid supported by renewable energy sources. While this may imply the hydrogen is not strictly green, an alternative approach could involve modeling the grid as a Power Purchase Agreement (PPA) contract sourced from a sustainable energy provider, which could be contracted via a third-party.

Regarding energy sources, a wide range of options exists, primarily dependent on the availability of the resource. As the priority is to produce green hydrogen, components that do not align with this premise were excluded from consideration. Specifically, (HassanzadehFard *et al.*, 2020) and (Vo *et al.*, 2022) incorporated Steam Methane Reformer fed by natural gas, (Wang *et al.*, 2022) utilized a gas boiler and turbine (GT) in their generation matrix to fulfill energy demands, while (Kilic and Altun, 2023) employed a diesel generator. It is important to emphasize that these technologies are not considered in this study since they are not in line with the objective of producing green hydrogen. Additionally, (Şevik, 2022) integrated the latter two technologies with PV generation to economically analyze the system's behavior on a university campus. Their simulation revealed reduced GHG emissions, putting emphasis on the fact that achieving sustainability goals depends not only on a mix of clean solutions but also on appropriate resource allocation, even with the inclusion of less clean technologies.

Currently, photovoltaic (PV) and wind energy are the most commonly studied sources, largely due to the widespread interest among project developers and government-led generation expansion plans in deploying these technologies on a large scale. Notably, studies by (HassanzadehFard *et al.*, 2020; Schnuelle *et al.*, 2020; Gao *et al.*, 2022; Zhang *et al.*, 2022, 2023; Kilic and Altun, 2023) constitute 25% of the literature review and emphasize the complementary nature of both PV and wind technologies, resulting in favorable outcomes for generating clean hydrogen. However, the integration of both solutions into a large-scale hydrogen production facility poses challenges for project developers, which is why this option was not further explored in this study.

Seventeen papers focused on solar generation, while 12 papers explored wind generation as part of their study. Considering the feasibility of these projects, it appears more practical for project developers to pursue a PV-Electrolyzer system rather than a Wind-Electrolyzer system. Therefore, solar PV is likely to offer more achievable results in terms of obtaining permits and ensuring financial and economic viability in the short term.

Apart from solar and wind, other renewable energy sources investigated for green hydrogen production included solar collectors (SC) as studied by (Yang,

Zhang and Lin, 2015; Mehrenjani *et al.*, 2022; Zhang *et al.*, 2023) as well as hydro and biogas as explored by (Ji *et al.*, 2023).

After analyzing the literature and recognizing the crucial components of contemporary multi-energy systems, this study will concentrate on a particular hybrid power system incorporating PV panels, grid access with the potential for injection, a battery storage system, and a PEM electrolyzer. Each of these elements will be explored in subsequent subsections, detailing the assumptions and considerations guiding their integration. Additionally, a comprehensive review of the auxiliary processes in the hydrogen chain, referred to as the Balance of Plant (BOP), will be conducted.

2.3.1 Renewable Energy Input: Solar Photovoltaic

A solar photovoltaic (PV) system harnesses solar energy to produce electricity, and its size can vary depending on its intended use, ranging from small-scale applications for homes to large power plants. These PV systems can be implemented in both off-grid and on-grid configurations. (Lu, Li and Li, 2023) states that the most common PV panel technologies for this application are monocrystalline, polycrystalline, and thin-film panels, each offering distinct advantages and characteristics.

In their research, (Matute *et al.*, 2022) considered the PV plant as the first and preferred energy source for the electrolyzer due to its advantageous aspect of representing no additional operational costs to the entire system. This is because the electricity is readily available as long as the PV plant is installed. The PV plant setup is comprised by photovoltaic modules, a solar tracker, and inverters that deliver electricity in AC.

By determining the location through latitude and longitude and using the plant's orientation provided via azimuth and inclination, it is possible to obtain reliable solar generation data for a year with an hourly resolution from (Renewables Ninja, 2020). As a result, the research model employed in this study allows for precise hourly analysis. Further details regarding the specific solar profile will be elaborated in the modelling subchapter.

According to (Gallardo *et al.*, 2021), the growing interest in utilizing off-grid PV-PEM systems for green hydrogen production (although this concept can also be applied to grid-connected systems) can be attributed to various factors. These include the escalating costs of conventional fuels, the imperative need to reduce dependence on fossil-based generation to address environmental concerns, the priority placed by EU members on ensuring security of supply, and the significant technological advancements in the efficiency of hydrogen production through electrolysis over the past decades.

In their work, (Gallardo *et al.*, 2022) explore the solar hydrogen production scheme represented by Figure 4. This system involves coupling a solar PV system with PEM electrolyzers through an AC link. The PV panels generate

electricity, which is then converted from DC to AC using an inverter. A portion of this electricity is consumed by various processes collectively known as Balance of Plant (BoP). These processes encompass rectifiers, power-electronic loads, water pumping and treatment, cooling systems, H₂ purification systems, safety, control, and lighting loads. The remaining electricity is directed back to the rectifier to be converted back to DC current, which is then fed into the PEM electrolyzer to produce hydrogen.

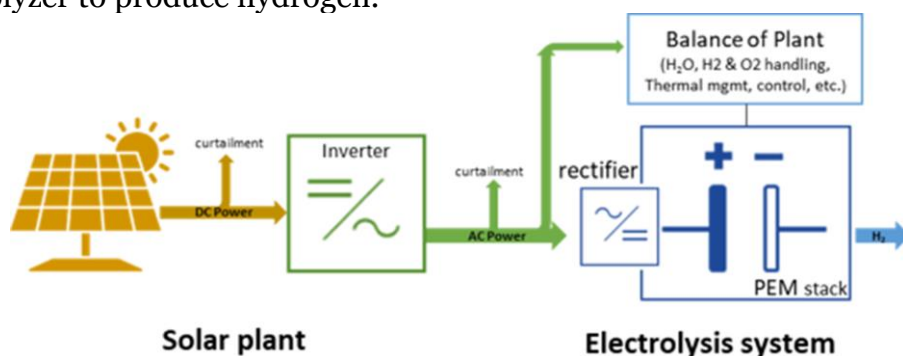


Figure 4. Solar-Hydrogen production scheme (Gallardo et al., 2022)

2.3.2 Battery Storage: Lithium-Ion Batteries

Ross underlines the importance of Li-Ion battery as we know it, by what was said during the 2019 Nobel Prize in Chemistry to Stanley Whittingham, John Goodenough and Akira Yoshino (Ross, 2022). The citation for the award said of the lithium-ion battery: ‘This lightweight, rechargeable and powerful battery is now used in everything from mobile phones to laptops and electric vehicles. It can also store significant amounts of energy from solar and wind power, making possible a fossil-free society.’

Warner provides insights into the operation of Lithium-ion batteries (LiBs) (Warner, 2019). It states that anode and cathode behave like a magnet's opposite poles, in the sense that lithium-ions move backwards and forward, exchanging lithium-ions between them and simultaneously releasing electrons, resulting in the flow of current. The composition of a LiB also contains a layer of charge in the metal electrode and a layer of charge in the electrolyte, creating an "electrical double layer" between electrodes, as depicted in Figure 5.

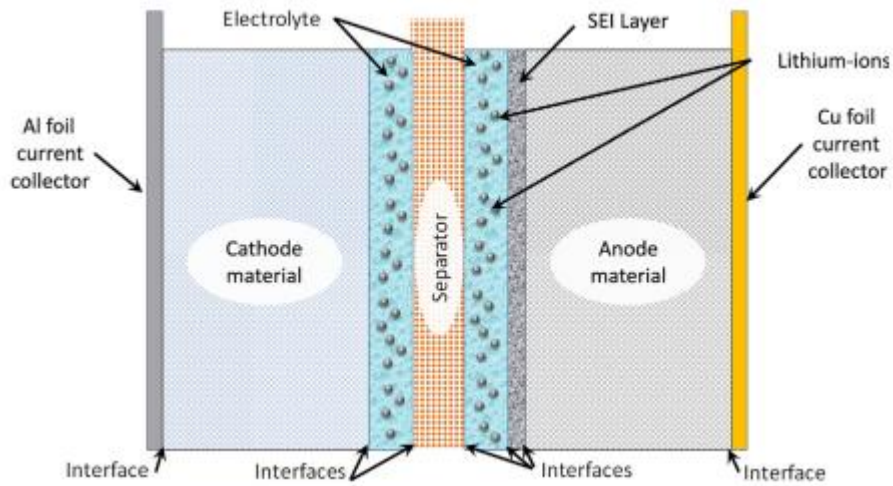


Figure 5. Lithium-Ion battery representation (Warner, 2019)

It is important to highlight that the reduction reaction exclusively occurs at the cathode, while the oxidation reaction takes place at the anode. However, due to the rechargeable nature of these batteries, both ends can interchangeably function as either the anode or cathode during charging or discharging. Typically, the cathode material comprises Lithium-Nickel-Manganese-Cobalt-Oxide (LiNiMnCoO_2), denoted as NMC, or Lithium iron phosphate or lithium ferro-phosphate (LFP), while the anode is usually graphite.

Figure 6 visually represents the operating principle of a LiB during the charge and discharge processes. As the anode releases its free electrons, the cell becomes discharged. During this phase, positive lithium ions travel from the anode to the positive cathode through the electrolyte, while electrons flow through the external circuit in the same direction.

Conversely, during the charging process, the opposite reactions occur. Applying a current into the cathode releases electrons, which pass through the circuit and into the anode material, thus charging the battery.

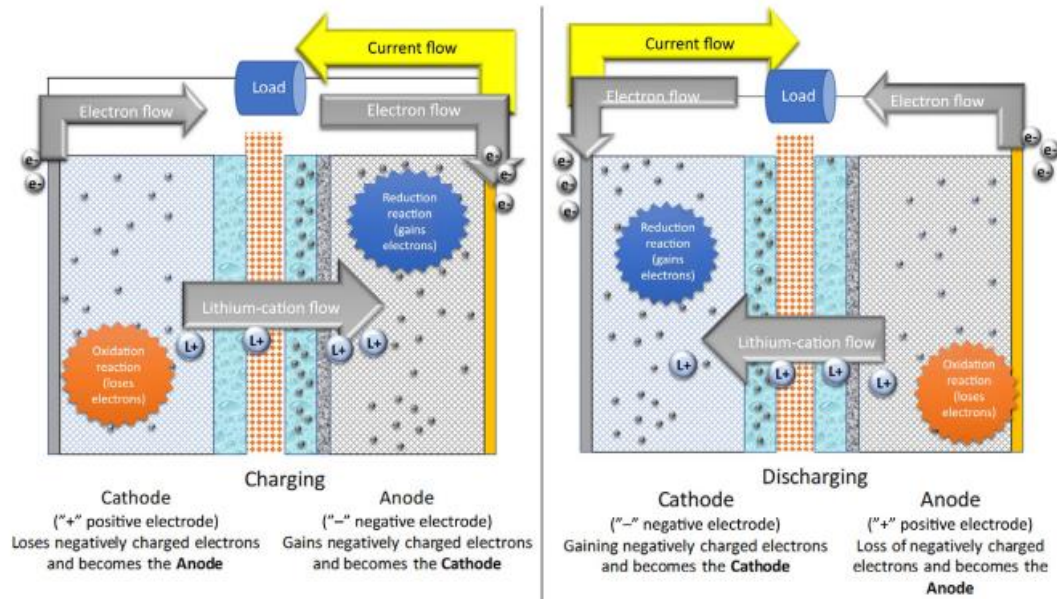


Figure 6. Charging and discharging phenomena in a Lithium-Ion battery (Warner, 2019)

According to (Wang *et al.*, 2021), the discharging behavior of lithium-ion batteries can be influenced by several factors, such as the depth of discharge, ambient temperature, and internal battery temperature, which contribute to the aging process. Additionally, the discharging characteristics can be affected by variables like charge-discharge current rate, discharge time, and other related factors.

In (Komorowska *et al.*, 2022)'s research, the focus was on examining the integration of Li-Ion batteries within a hydrogen application, particularly concerning price arbitrage in the day-ahead market. The findings indicated that utilizing a Li-Ion battery in Poland's electricity market was not financially viable at the time of the study. However, there is optimism for the future, as it is projected that battery production costs may decrease by 75% in the upcoming 15 years, potentially leading to more favorable outcomes.

According to (DeMeuse, 2021), the lithium-ion battery (LiB) offers evident advantages, and extensive research has transformed it into a high-energy density, long-life cycle, and efficient battery as it stands today. Nevertheless, ongoing research persists in exploring novel battery component materials, aiming to push the boundaries in terms of cost, energy density, power density, life cycle, and safety. Due to their versatility and widespread applications in energy storage, LiBs are likely to retain significant commercial importance for an extended period.

2.3.3 Electrolyzer Technology

Electrolysis of water involves the application of a direct current (DC) where electrons flow from the negative terminal of the DC source to the cathode. As explained in (Sebbahi *et al.*, 2022), at the cathode, the electrons are consumed

by hydrogen ions present in the water, resulting in hydrogen gas. To maintain charge balance within the cell, the hydroxide ions produced during the cathodic reaction move to the anode. At the anode, these hydroxide ions lose electrons, which return to the positive terminal of the DC source, and oxygen gas is produced. The primary water electrolysis technologies currently available in the industry are alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and the solid oxide electrolyzer cell (SOEC). A schematic illustrating these different technologies is presented in Figure 7.

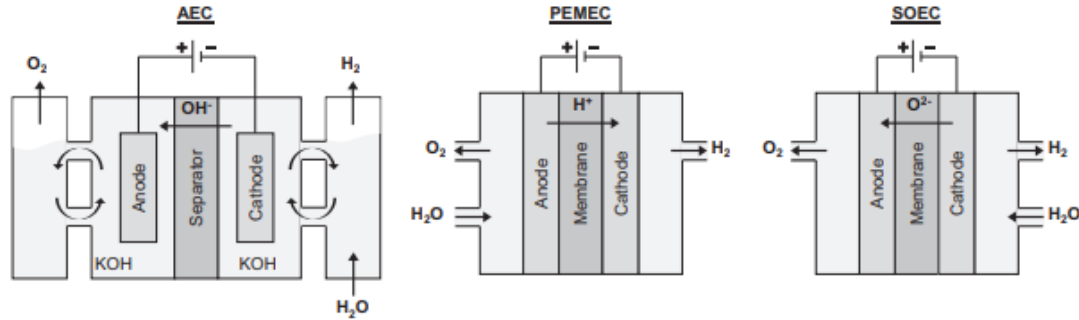


Figure 7. Conceptual set-up of the major electrolysis cell technologies (Schmidt *et al.*, 2017)

According to (Sebbahi *et al.*, 2022), the AWE technology commonly utilizes water solutions containing potassium hydroxide (KOH) and sodium hydroxide (NaOH) as the electrolytes. An essential component of this technology is the membrane separator. During the electrolysis process, hydrogen gas is liberated at the cathode (where water is reduced), leading to the formation of hydroxide anions. These hydroxide anions then pass through the diaphragm and move towards the anode, driven by the electric field established by the external power source. On the anode side, these hydroxide anions recombine, resulting in the production of oxygen gas and the release of electrons.

PEM electrolysis cells share similarities with AWE cells, but they utilize a solid polymer electrolyte membrane with an acidic nature instead of an alkaline aqueous electrolyte. This membrane, together with the electrodes, forms the membrane electrode assembly (MEA) as described in (Santos, Cebola and Santos, 2021). The electrolysis process involves water oxidation at the anode, leading to the generation of oxygen, electrons, and protons. These ions then pass through the membrane to the cathode, where they are reduced, thereby closing the circuit and producing hydrogen, which is subsequently released to the gas manifold at the cathode, as mentioned in (Sebbahi *et al.*, 2022).

SOEC technology, as explored in (Sebbahi *et al.*, 2022), allows for the co-electrolysis of CO₂ and steam. Unlike alkaline and PEM methods, SOEC systems operate at higher temperatures, typically ranging from 500°C to 1000°C. In these systems, both steam and recycled hydrogen are supplied to the cathode, where water is reduced to produce hydrogen. The oxide anions formed in the cathode then flow through the solid electrolyte to the anode, where they recombine to form oxygen and close the circuit with the liberated electrons. Notably, these reactions take place when the electrodes are in contact

with a gas or vapor phase, a feature that distinguishes SOEC from alkaline or PEM electrolyzers.

Table 3 compiled by (Santos, Cebola and Santos, 2021) illustrates the main specifications from the discussed electrolyzer technologies. The technology efficiency can be interpreted as the inverse of the specific system energy consumption (SEC), therefore, the technology with the highest SEC would yield the lowest electrolyzer efficiency.

Specifications	AWE	PEM	SOEC
Operating temperature ($^{\circ}\text{C}$)	60–80	50–84	650–1000
Operating pressure (MPa)	<3	<3	<3
Current density (A cm^{-2})	0.2–0.5	0.6–2.2	0.3–2.0
Cell voltage (V)	1.8–2.4	1.8–2.2	0.7–1.5
Voltage efficiency (%)	62–82	67–82	81–86
Production rate ($\text{m}^3_{\text{H}_2} \text{h}^{-1}$)	<760	<40	<40
Specific system energy consumption (kWh Nm^{-3})	4.3–4.8	4.4–5	2.5–3.5
Hydrogen purity (%)	99.7–99.9	99.999	99.9
Cell area (m^2)	3–3.6	<0.13	<0.06
Minimum partial load (%)	10–40	0–10	-
Stack lifetime (kh)	55–120	60–100	8–20
System lifetime (years)	20–30	10–20	-
System response	s	ms	s
Cold-start time (min)	<60	<15	<60
Capital cost * (€ kW^{-1})	620–1170	1090–1650	>1560

Table 3. Main specifications of the different electrolysis technologies (Prices for 2020) (Santos, Cebola and Santos, 2021)

In summary, the following are the advantages and disadvantages of each technology based on (Sebbahi *et al.*, 2022) and (PtX Hub, 2021).

2.3.3.1 Alkaline Water Electrolysis (AWE)

- Advantages:
 - Mature technology.
 - Longer lifetime.
 - Low capital cost.
 - High stability.
 - Does not require critical raw materials.
 - Suitable for large-scale plants with high nominal output (>100MW).
- Disadvantages
 - Vulnerable to impurities in product gases.
 - Long cold start time (approx. 50 min).
 - Corrosivity of the electrolyte.
 - Lower current density.

2.3.3.2 Proton Exchange Membrane (PEM)

- Advantages:
 - Commercially ready.
 - Highest purity hydrogen.

- Ideal for intermittent renewable energy sources due to good dynamic properties.
- Quick response/start time (approx. 15 min).
- Compact and simple design.
- High current density.
- Disadvantages
 - Electrodes made of critical metals.
 - Higher investment costs.
 - Lower durability.
 - Acidic medium.

2.3.3.3 Solid Oxide Electrolyzer Cell (SOEC)

- Advantages:
 - Highest efficiency (80%).
 - Suitable for co-electrolysis: Direct synthesis gas generation.
 - Can be integrated with heat streams.
 - Low capital costs.
 - Without precious catalyst.
 - High current density.
- Disadvantages
 - Still in the demonstration stage.
 - Instability of electrodes.
 - Safety problems.
 - Long cold start time, possibly lasting several hours.

The diverse strengths and weaknesses of different technologies are intriguing to observe, and it becomes evident that no single solution will dominate the market. Instead, each technology's development should be tailored to its appropriate application. Among them, PEM stands out as particularly well-suited for integration with renewable energy sources, making it the focus of further modeling and utilization in this report.

Based on expert elicitations conducted by (Schmidt *et al.*, 2017), a notable shift from AWE to PEM systems as the primary technology for electrolysis coupled with renewable sources is anticipated by the majority of experts. The investment costs have already shown significant reductions by 2020. However, PEM's higher operational flexibility is expected to propel it to become the leading commercial technology by 2030. As for SOEC advocates, they envision (albeit with some uncertainty) this technology eventually reaching cost and lifetime figures comparable to AWE and PEM systems.

2.3.4 Balance of Plants (BOP)

The technological scheme of a PEM electrolysis system, as presented by (Olivier, Bourasseau and Bouamama, 2017) in Figure 8, reveals the complexity of the electrolysis process, involving various components and several physical phenomena occurring at different stages. Their study concludes that electrolysis exhibits intricate and nonlinear behavior due to two primary

reasons. Firstly, it involves multi-energy coupling, non-stationarity, and spatiotemporal dynamics. Secondly, the evaluated models thus far primarily adopt a systemic approach, with a focus on stack description using ordinary differential equations.

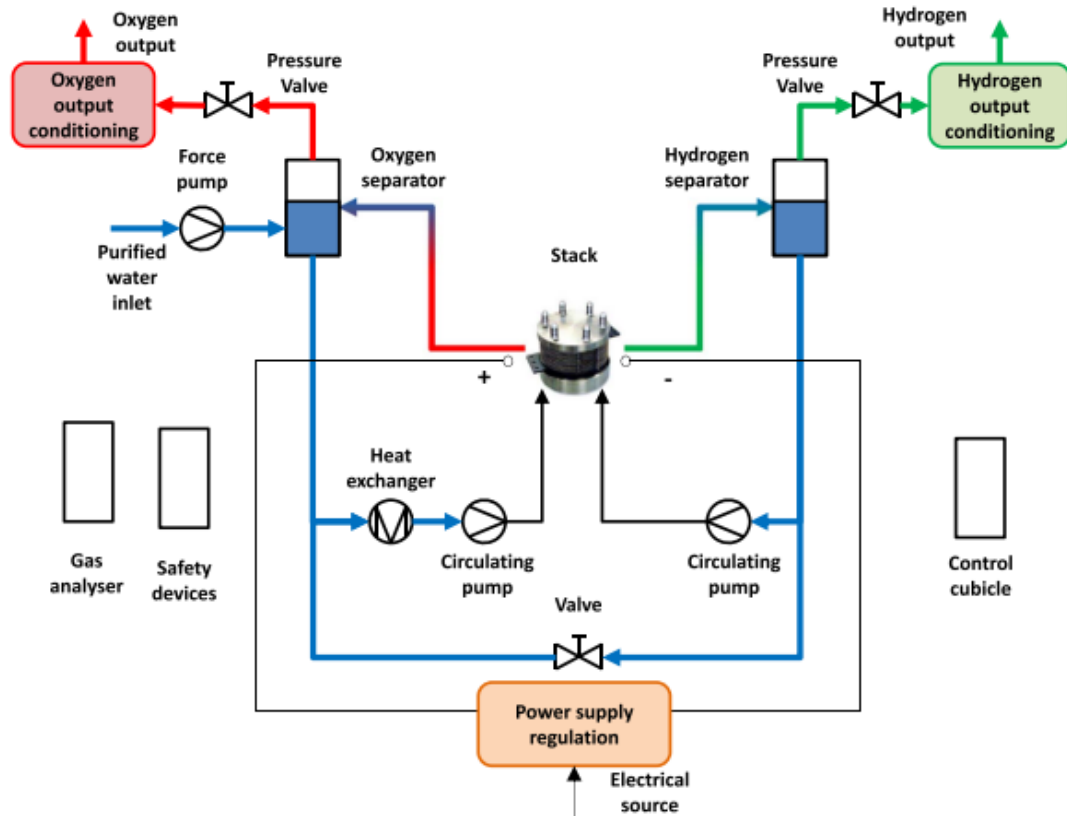


Figure 8. Technological scheme of a PEM electrolysis system (Olivier, Bourasseau and Bouamama, 2017)

On an aggregated level, figure 9 by (Hancke, Holm and Ulleberg, 2022) illustrates a block diagram of the PEM electrolyzer setup. The components considered are:

- Stack: N cells connected in series
- Rectifier: Responsible of supplying the electrolyzer with DC current.
- Water circulation pump: Supplies the anode with deionized water at the operating temperature.
- Hydrogen dryer: A chemical adsorption system. The drying process is conducted in two steps: The first step is condensation drying by cooling the gas with ambient air to a temperature of 30 °C. In the second step, adsorption drying lowers the water content in the product gas to the desired level
- Mechanical compressor.

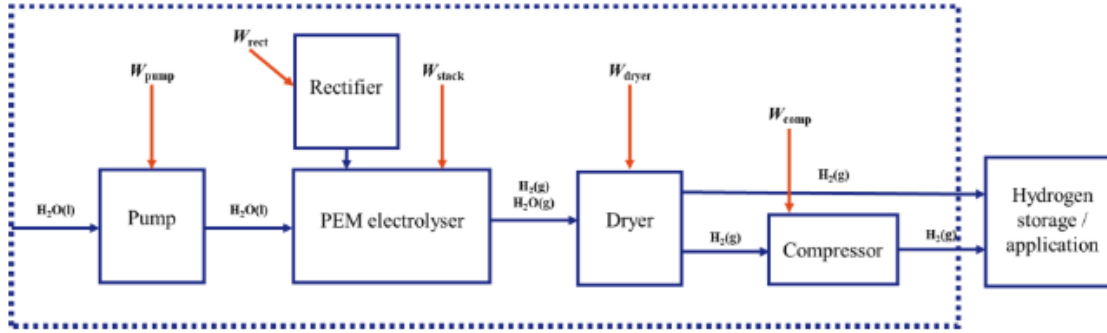


Figure 9. Components on an aggregated level in a PEM electrolyzer setup (Hancke, Holm and Ulleberg, 2022)

The system work, which stands for the total energy demand per unit mass of net hydrogen, is the addition of the different element's work plus an additional miscellaneous term which refers to the use of auxiliary equipment and processes (e.g. measuring devices, startup heaters).

In a simulation conducted by (Hancke, Holm and Ulleberg, 2022) considering these subsystems, the results indicated that in a 10 MW PEM system, where hydrogen is produced at 30 bar and then mechanically compressed to 700 bar, approximately 89% of the total energy consumption was attributed to the electrolyzer, while the remaining processes accounted for the remaining 11%. Although current PEM systems typically operate at hydrogen outlet pressures of 30 bar, this figure offers valuable insights into the energy consumption patterns of the various components.

A noteworthy observation regarding the operational decisions concerning various variables in the multiple inherent processes of hydrogen production is made by (Tjarks *et al.*, 2018). His study, primarily focused on hydrogen drying and compressing, underscores the significance of achieving high efficiency and minimizing the specific energy demand in hydrogen production for economically viable power-to-gas applications. Striking the right balance between the energy requirements for hydrogen production and gas conditioning is crucial in this regard.

2.4 Optimization Algorithm

Yang *et al.* conducted a study on various optimization methods used for sizing and placing energy storage systems in power grids (Yang *et al.*, 2020). Although this thesis primarily focuses on energy dispatch rather than sizing or placement, the similarity in the nature of the problems allows for cautious interpolation of their results into the dispatch optimization issue in power grids. Notably, the common characteristics of these optimization problems include an objective function that typically considers economic criteria and a set of constraints defined by the technical limits of the studied technologies, such as ramp-up, ramp-down, and installed capacity. Additionally, these problems take into account the influences of the energy market, with inputs often involving factors

such as electricity prices, demand equal to generation at each time step, and other market-related parameters. It is worth noting that a consistent feature among these problems is that the parameters' rate of change remains consistent, as the type of assets falls within the same magnitude levels, further contributing to the applicability of these approaches in the energy market context.

AUTHOR	OPTIMIZATION METHOD	ALGORITHM	FOCUS
<i>(Liaqat, Rehman and Ahmad, 2020)</i>	Analytical	N/A	Component Design, experimental
<i>(Ji et al., 2023)</i>	Analytical	N/A	Modelling, economic,
<i>(Gallardo et al., 2022)</i>	Analytical	N/A	Modelling, Operation, Economic
<i>(Schnuelle et al., 2020)</i>	Analytical	N/A	Modelling, Operation
<i>(Rezaei, Khalilpour and Mohamed, 2021)</i>	Analytical	N/A	Economic modelling
<i>(Mohammadshahi et al., 2022)</i>	Analytical	N/A	Modelling, Operation
<i>(Yang, Zhang and Lin, 2015)</i>	Analytical	N/A	Modelling, Operation, Economic
<i>(Zghaibeh et al., 2022)</i>	Analytical	N/A	Design, operation, economic
<i>(Şevik, 2022)</i>	Analytical	N/A	Modelling, economic
<i>(Vo et al., 2022)</i>	Artificial Neuron Network	N/A	Modelling, Operation
<i>(Gao et al., 2022)</i>	Hybrid	Copula - MILP	Modelling, Operation, Economic
<i>(Marocco et al., 2021)</i>	Mathematical	MILP	Design, optimal sizing
<i>(Wang et al., 2022)</i>	Mathematical	MINLP	Modelling, Operation
<i>(Mehrenjani et al., 2022)</i>	Mathematical	LP Multidimensional Pareto	Design, modeling, economic
<i>(Matute et al., 2022)</i>	Mathematical	MINLP	Modelling, Operation, Economic
<i>(Phan-Van, Takano and Nguyen Duc, 2023)</i>	Meta-Heuristic	Artificial Bee Colony	Optimal sizing
<i>(Wang and Zhang, 2023)</i>	Meta-Heuristic	Artificial Bee Colony	Design, economic
<i>(Lu, Li and Li, 2023)</i>	Meta-Heuristic	Swarm Particle Optimization	Design, operation
<i>(HassanzadehFard et al., 2020)</i>	Meta-Heuristic	Swarm Particle	Design, Operation
<i>(Zhang et al., 2022)</i>	Meta-Heuristic	Improved NSGA-II	Optimal sizing

(Hong, Wei and Han, 2022)	Meta-Heuristic	Artificial Bee Colony	Modelling, operation, economic
(Grüger et al., 2019)	Meta-Heuristic	Not Specified	Operation, economic
(Kilic and Altun, 2023)	Probabilistic	Taguchi	Modelling, Operation, Economic
(Zhang et al., 2023)	Probabilistic	Chance Constraint Programming (CCP)	Modelling, operation, economic

Table 4. Review on similar hydrogen-based energy systems, organized by optimization method, algorithm and focus

The one-stop handbook introduced by (Yang *et al.*, 2020) identifies six major optimization methods: analytical methods, probabilistic methods, mathematical methods, meta-heuristic methods, artificial neural network methods, and hybrid methods. Table 4 lists the different optimization methods used by the authors studied in the literature review and their respective focus.

Analytical methods (AMs) excel in optimization by formulating algebraic functions and employing repetitive calculations or simulations at fixed intervals, considering varying power and energy capacity. AMs utilize advanced algorithms like parallel branch and bound, benders decomposition, and others. However, for this research, AMs will not be considered due to their prolonged convergence time caused by computational complexity and their tendency to get trapped at local optima.

Probabilistic methods (PMs) are widely used algorithms for managing uncertainties in energy systems. They can be categorized into two types: chance-constrained methods and stochastic optimization methods. The former involve managing tolerance ranges for technical criteria and present a challenge to calculate their probability distribution functions (PDFs) based on known PDFs, like wind power outputs, thus, requiring to linearize. The latter, which have methods such as Monte-Carlo simulation or Markov-Chains, use representative samples of random variables and aim to find solutions with optimal performance across the different scenarios.

Mathematical optimizations (MOs) refer to numerical methods for seeking optimal solutions through an approximated model, where the objective function is evaluated iteratively and stops when the best result is achieved. MOs encompass dynamic programming (DP), linear programming (LP), mixed-integer linear programming (MILP), interior point algorithm (IPA), and more. A significant advantage of MOs over other methods lies in their efficient solvability using off-the-shelf solvers like general algebraic modelling system (GAMS), CPLEX, Gurobi, and others. However, MOs are generally unsuitable for non-linear, large-scale, and long-term energy storage system (ESS) problems.

Meta-heuristic algorithms (MhAs) are known for their flexibility, as they do not rely on specific models and can avoid getting trapped in local optimum solutions. Some examples of meta-heuristic algorithms include genetic

algorithms, particle swarm optimization, simulated annealing algorithm, and firefly algorithm. However, these algorithms tend to have lower efficiency when it comes to handling constraints. Since individuals are generated randomly, updating the population with respect to constraints can become complex. As a result, these algorithms might not be the most suitable choice for this specific study on green hydrogen production involving various assets that provide different constraints.

Artificial neural networks (ANN) are renowned for their ability to model complex mappings, recognize patterns, approximate functions, and perform classifications. These networks can be trained to quickly predict and generalize, making them valuable tools in various applications, for example they can transform highly non-linear models into a simpler input-output form, unlike AM or MO. Moreover, they excel in generating high-quality forecasts that are robust and resistant to noise.

However, there are some complex and time-consuming challenges associated with adopting artificial neural networks. One of the main issues lies in selecting an appropriate architecture, such as neuron connection patterns, network parameters, and learning rates. In the specific implementation of this research, the main obstacle was the requirement for a vast amount of historical data, given the novelty of the solution and the unique configuration of the system, acquiring such data would be challenging.

Given that our problem can be formulated as a linear one, and our priorities include obtaining high-quality solutions, achieving fast convergence, and ensuring strong robustness for linear problems, the MILP method was chosen to proceed with the optimal dispatch of the green hydrogen problem.

Hybrid methods (HMs) are ideal to complement the strengths of the previously described methods and reach enhanced performance. For example, to determine the optimal sizing of the proposed system, which is outside the scope of this study, it could be proposed a meta-heuristic method for the sizing iterative part and the MILP method for determining in an hourly basis the optimal dispatch. Another option could be in case the optimal dispatch algorithm is implemented in a real operative system, to integrate an artificial neuron network to forecast the inputs as energy price, weather and based on those optimize the dispatch.

Hybrid methods (HMs) offer a promising approach to capitalize on the strengths of the previously described methods and achieve improved performance. For instance, when determining the optimal sizing of the proposed system, a combination of approaches can be employed. A meta-heuristic method could be utilized for the iterative sizing part, while the MILP method could be applied to determine the optimal dispatch on an hourly basis. This combination allows for a comprehensive and effective approach to handle the system's optimization tasks.

Another viable option is to integrate an artificial neural network (ANN) into the optimal dispatch algorithm when implementing it in a real operative system. The ANN can be employed to forecast crucial inputs such as energy prices and weather conditions. By leveraging these forecasts, the dispatch algorithm can optimize the system's operation based on anticipated variations, resulting in enhanced efficiency and cost-effectiveness. These hybrid strategies showcase the potential for maximizing the advantages of different methodologies, leading to superior outcomes in various applications.

3 Knowledge Gap and Objectives

3.1 Objectives

This thesis is driven by two central objectives, which are outlined as follows:

- i. To develop a methodological framework for evaluating the optimal dispatch of a water-electrolysis project integrated with renewable energy generation, a battery storage system, and grid interaction for electricity injection. The primary aim is to determine the solution that maximizes the net profit, taking into account various factors and constraints.
- ii. To employ the chosen optimization model to analyze specific case studies and effectively evaluate hydrogen projects based on techno-economic criteria. Additionally, identify and examine the limitations inherent in the model, thus gaining insights into its applicability and potential areas for improvement.

3.2 Research Questions

This thesis has been meticulously formulated to address the three research questions outlined below:

- i. What are the existing methodologies and techniques available for achieving the optimal dispatch of hydrogen production when integrating water-electrolysis projects with renewable energy generation, battery storage systems, and grid interaction?
- ii. How do the optimization results vary when applied to locations with abundant solar, wind, or hydro resources? Do the economic indicators demonstrate cost-competitive solutions that align with the energy context of the selected location?
- iii. How do different techno-economic criteria impact the evaluation of hydrogen projects? Can the chosen optimization model effectively capture the nuances and complexities of various techno-economic aspects, such as investment costs, operational expenses, and revenue streams, to provide robust and insightful assessments?

3.3 Knowledge Gap

The existing literature review reveals a notable knowledge gap concerning the specific focus of this study, which centers on a simplified system configuration. The majority of studies found in the literature primarily concentrate on the optimal sizing and placement of energy storage systems. While some investigations do consider hydrogen as an energy storage system, they tend to be more generic in nature and lack a comprehensive examination of the interplay between a green hydrogen production facility and battery storage.

Although dispatch optimization has been extensively explored in various research papers, a distinct research gap becomes evident when it comes to its direct application to green hydrogen production. The unique aspect that sets green hydrogen apart is the exclusive utilization of energy derived from renewable sources. Thus, studies addressing the dispatch optimization of a system involving green hydrogen production, with a specific emphasis on the intricate relationship between the renewable energy sources and the production facility, are notably scarce in the existing literature. Consequently, there exists a critical need to bridge this knowledge gap and develop a deeper understanding of the optimal dispatch strategies tailored specifically for green hydrogen systems.

Furthermore, it is essential to highlight that this study goes beyond the conventional approach of bolstering solar generation alone. In addition to enhancing solar generation capacity, this research also considers the potential establishment of hydrogen hubs strategically positioned to meet the evolving needs of potential offtakers. This holistic approach aims to address the broader spectrum of challenges and opportunities associated with the integration of green hydrogen production into renewable energy systems.

3.4 Limitations

Firstly, the model employed in this research does not incorporate hydrogen storage, which can be a critical component in real-world hydrogen production systems. The omission of hydrogen storage is due to the complexity it introduces into the optimization framework and the aim to simplify the model for an initial exploration of optimal dispatch strategies.

Secondly, the study does not account for non-linear factors that may influence the performance of the system, such as the dynamic efficiency of the Proton Exchange Membrane (PEM) electrolyzer and stack degradation, nor does it consider battery degradation. Incorporating these non-linear factors would provide a more accurate representation of real-world operations but would significantly increase the complexity of the optimization model.

Furthermore, it is important to note that this study does not perform an optimal sizing of the system components. Instead, it focuses on evaluating the system's

performance and profitability based on chosen sizes for the assets. While this approach provides valuable insights, it does have limitations. The study optimizes the dispatch based on an established configuration, and although sensitivity analyses are conducted to assess the impact of different asset sizes, it may not capture the full spectrum of potential configurations and their associated benefits or drawbacks.

4 Methodology

This section provides a comprehensive overview of the system modelling for each specific subsystem analyzed in the problem statement. These subsystems encompass the electrolyzer, the battery system, the solar panels, and the grid. Additionally, a subsequent chapter elucidates the optimization algorithm employed for dispatch optimization, along with the mathematical representation of the optimization problem. Lastly, a review of the key performance indicators, highlighting their significance and relevance in the context of this research.

4.1 System Model

The chosen model for the optimal dispatch incorporates grid connection, a PEM Electrolyzer, a solar power plant, and a Li-Ion battery storage system, as shown in Figure 10.

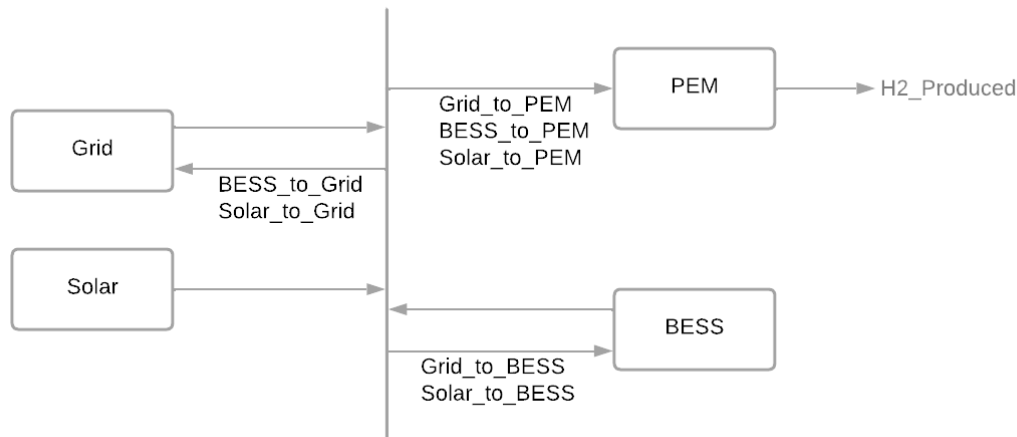


Figure 10. System Overview

Within the scope of this thesis, the energy flows expected from a PV connection to an electrolysis plant with BESS are as follows:

- **Solar_to_PEM:** The energy produced from the solar photovoltaic plant to feed the PEM electrolyzer.
- **Solar_to_BESS:** The energy produced from the solar photovoltaic plant to be stored in the battery.
- **Solar_to_Grid:** The energy produced from the solar photovoltaic plant and sold to the wholesale electricity market.

Regarding the BESS, the energy flows expected from and to the batteries in an electrolysis plant with PV and PEM electrolyzer are as follows:

- BESS_to_PEM: The energy stored in the batteries used to feed the PEM electrolyzer.
- BESS_to_Grid: The energy stored in the batteries to inject back in the grid.
- Grid_to_BESS: The energy from the grid that is stored in the battery.

Finally, the last energy flow comes from the grid as follows:

- Grid_to_PEM: The energy from the grid to feed the PEM electrolyzer.

This notation will be employed in the mathematical formulation of the problem and will also be used in the images provided in subsequent subchapters.

4.1.1.1 Study Cases

To evaluate the feasibility of the green hydrogen system and acknowledge its strong dependence on local context, two study cases have been selected for comparison: Sweden and Spain.

Both Sweden and Spain are part of the European Union (EU), sharing common policies and climate goals set by the EU. Additionally, they adhere to similar regulatory mechanisms, including the Emissions Trading Scheme (ETS) and other relevant initiatives. However, despite these similarities, the two countries present contrasting conditions concerning resource availability, particularly in terms of solar energy, and distinct market conditions.

Sweden, with its geographical location, offers different solar energy potential compared to Spain. The resource availability and climatic factors are decisive in shaping the renewable energy landscape, highlighting the significance of considering these local characteristics for the feasibility of the green hydrogen project.

Furthermore, each country's unique market conditions, energy demand patterns, and grid infrastructure further emphasize the importance of a context-specific approach. While the EU-wide policies provide a common framework, the divergent market dynamics in Sweden and Spain showcase how the project's viability is intricately tied to its local context.

Both Sweden and Spain have recognized the immense potential of green hydrogen and have national programs or agendas in place to promote its development extensively within their territories. These strategic efforts demonstrate their commitment to the transition towards sustainable and low-carbon energy solutions.

By analyzing and comparing the outcomes of the green hydrogen system in these two distinct contexts, valuable insights can be gained, shedding light on the factors that contribute to the project's success or challenges. This approach serves to showcase the relevance of context-specific considerations and contributes to the broader understanding of implementing green hydrogen technologies on a regional or national scale.

The hourly electricity price data for both countries was collected from the ENTSO-E (ENTSO-E, 2023) transparency platform. ENTSO-E functions as the European association that facilitates collaboration among transmission system operators (TSOs) responsible for electricity. This platform offers comprehensive information on electricity generation, transportation, and consumption within the pan-European market. The data utilized in this study is specifically from the year 2020.

To gather solar input data, the source utilized was Renewables Ninja (Renewables Ninja, 2020) a platform that enables simulations of hourly power output from wind and solar power plants worldwide. This tool was developed to provide scientific-quality weather and energy data to a broader community.

In the context of site selection, where ideal solar irradiation is crucial, Figure 11 displays Sweden's average solar radiation for the year 2018 (Lindahl and Stoltz, 2018), while Figure 12 illustrates Spain's average solar radiation for the period 1994-2018 (Solargis, 2023), highlighting regions with higher solar potential. However, choosing project locations involves a delicate balance between optimal solar irradiation and proximity to industry hubs or proposed hydrogen infrastructure. Therefore, the expansion plans of both projects were meticulously evaluated to identify locations that strike the right tradeoff between ideal solar irradiation and proximity to industry or planned hydrogen infrastructure development.

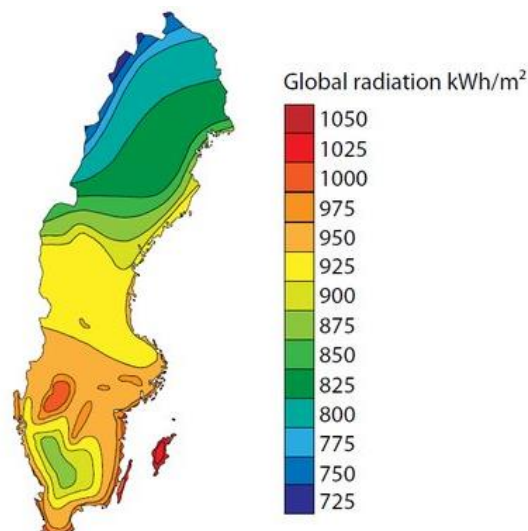


Figure 11. Global solar radiation in Sweden in one year (Lindahl and Stoltz, 2018)

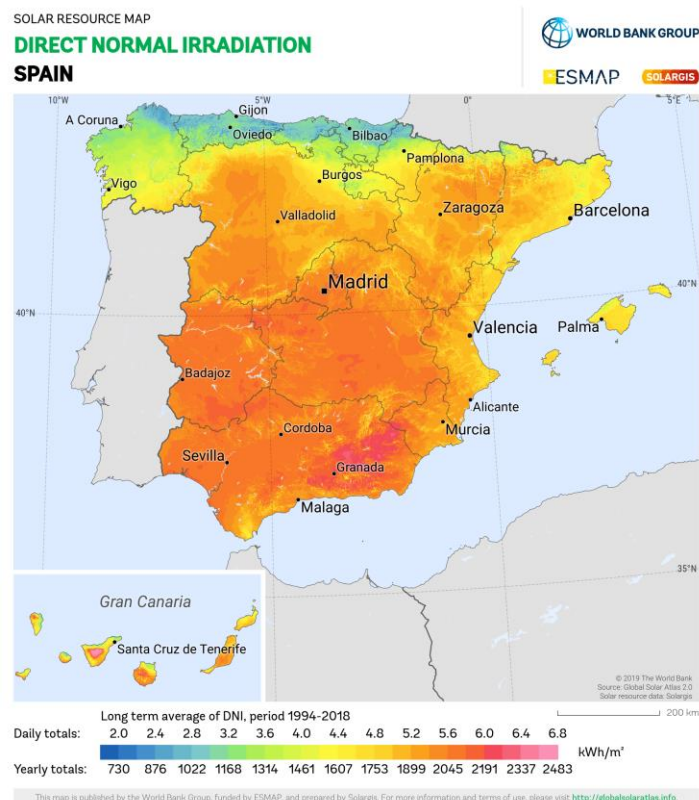


Figure 12. Photovoltaic power potential in Spain (Solargis, 2023)

Figures 13 and 14, respectively, showcase the expansion plans for Sweden (Fossilfritt Sverige, 2021) and Spain (Enagás, 2022). In the case of Spain, Valencia emerges as a strategic location for the 2030 expansion plan, while in Sweden, Sandviken was selected due to its proximity to industry and central position within the established hydrogen council in the Gävleborg and Dalarna region. This underscores the significance of a multifaceted approach to project development in the pursuit of sustainable hydrogen solutions.

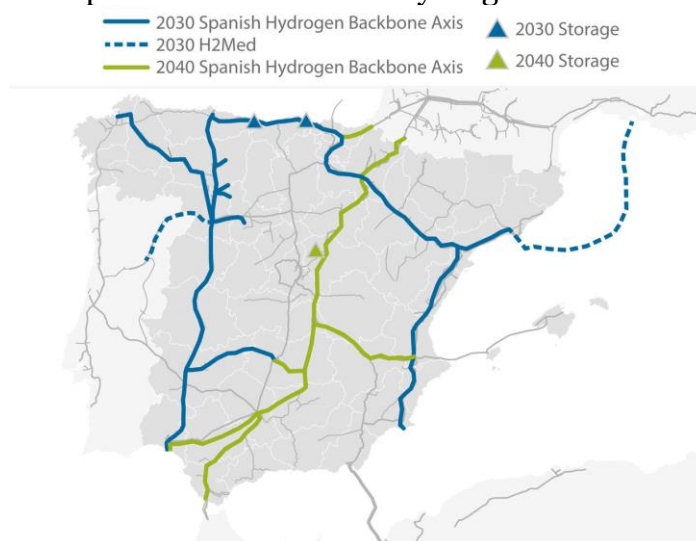


Figure 13. Basic hydrogen infrastructure proposed by Enagás for Spain in 2030 and 2040 (Enagás, 2022)

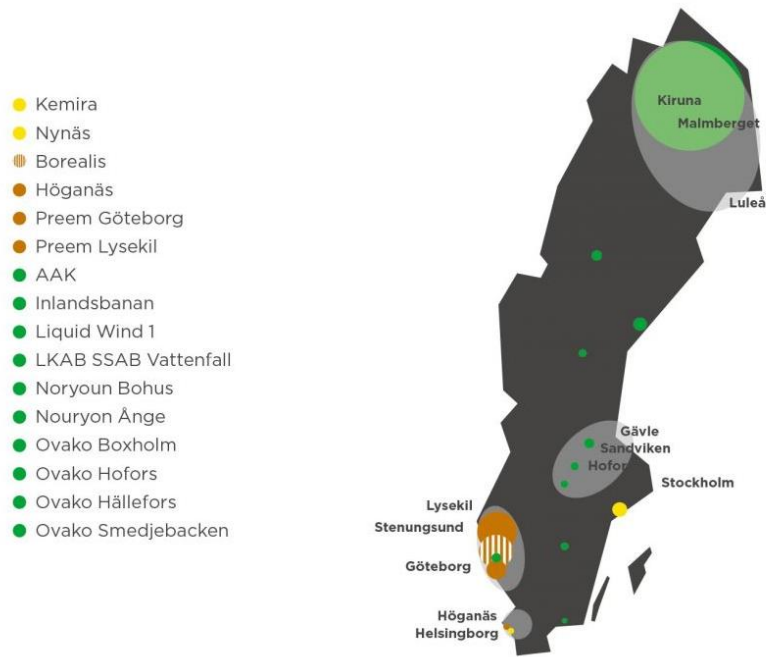


Figure 14. Examples of potential hydrogen clusters in Sweden based on concrete plans and projects (Fossilfritt Sverige, 2021)

To account for real-world operational losses in the solar power plants, a system loss of 0.1 was considered for both cases, using data from the MERRA-2 dataset. In both scenarios, a 130MWp power plant equipped with a 1-axis tracking system was employed. The tilt angle for the plant in Sandviken was set at 60° , while the one in Valencia had a tilt angle of 39° , with both having an azimuth of 180° .

4.1.1.1 Sweden

Figure 15 displays the electricity price trends in Sweden throughout 2020. The average price was recorded at around 11.4 EUR/MWh. It is essential to note that there were sporadic periods, particularly in September and October, where the price experienced sharp spikes, reaching as high as 189 EUR/MWh. Despite the occasional surges, the overall price behavior in Sweden remained relatively stable, with a standard deviation of 11.5 EUR/MWh.

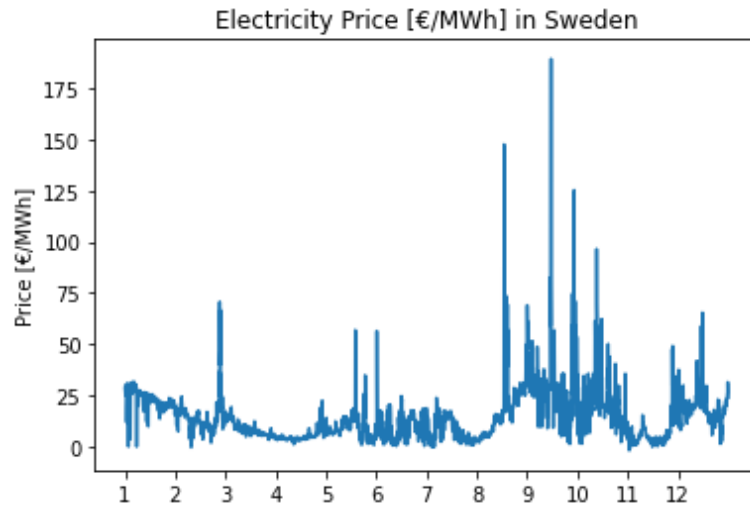


Figure 15. Day-Ahead market price in Sweden (2020)

Figure 16 displays the solar generation data from a solar plant in Sweden with an installed capacity of 130MWp. The trends depicted in the graph reveal that the solar generation reaches approximately 100MW during the summer months, while it typically drops to below 20MW during the winter months. The average power output is 20.5MW, with a standard deviation of 31.9MW.

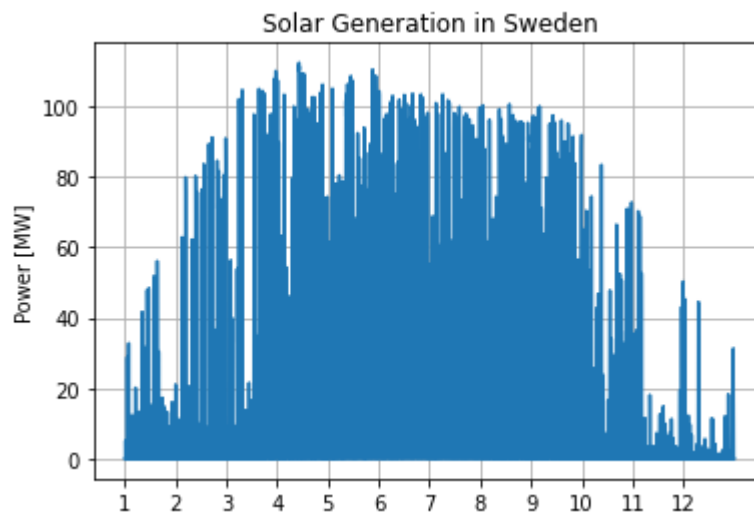


Figure 16. Solar Profile in Sweden (2019)

South Central Sweden, where Sandviken is located, is part of the Swedish energy pricing area S2. Figure 17 from (Electricity Maps, 2022) illustrates the green energy production in Sweden, revealing a 25gCO₂eq/kWh carbon intensity aggregated value in 2020. Impressively, 99% of Sweden's energy matrix consists of low-carbon sources, with renewables making up 60% of the total.

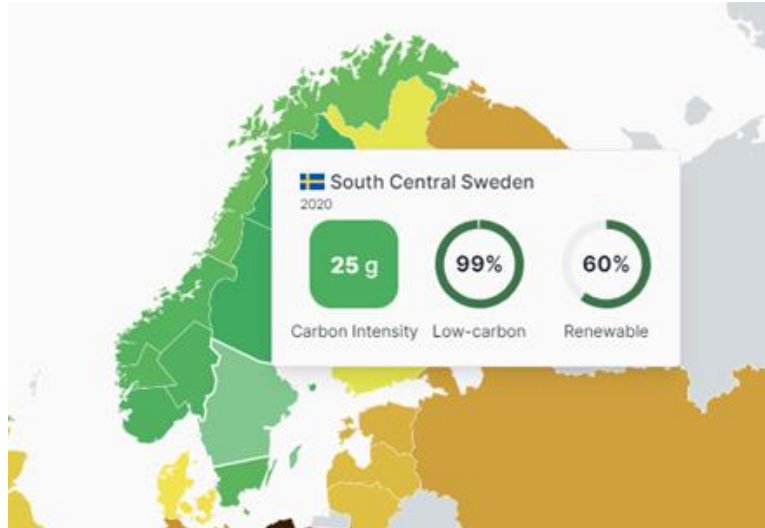


Figure 17. The national grid's aggregated carbon footprint for Sweden in the year 2020 (Electricity Maps, 2022)

4.1.1.2 Spain

The data presented in Figure 18 illustrates the hourly prices in Spain for the year 2020, indicating an average price of around 34 EUR/MWh and a standard deviation of 11.3 EUR/MWh. This data highlights the country experiencing strong seasonality, where the energy system exhibits different behaviors during winter and summer, reflecting the impact of varying energy demand and supply patterns during these seasons.

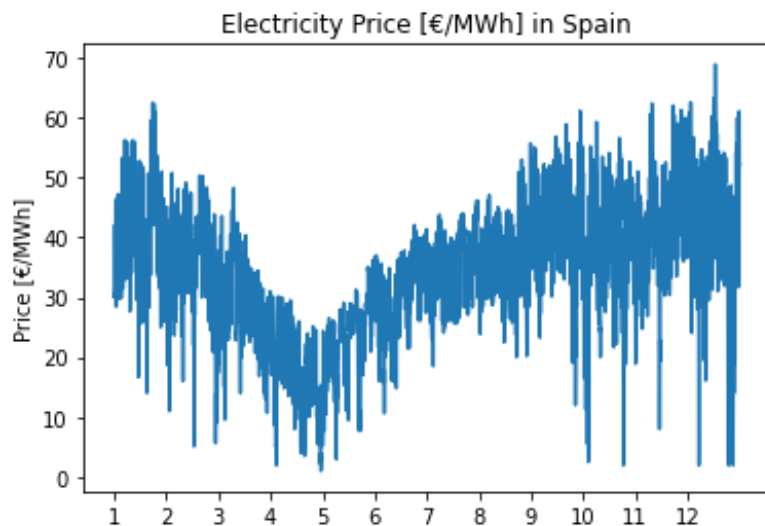


Figure 18. Day-Ahead market price in Spain (2020)

As for the solar profile analyzed in Spain depicted in Figure 19, the average solar generation is 33.2MW, exhibiting a higher mean compared to the Swedish case. Additionally, the standard deviation in Spain is 40MW, indicating more significant fluctuations in solar generation throughout the year. This higher resource availability in Spain suggests that the energy yield expected to power

the electrolyzer is greater than that of the Swedish case. Both countries, however, share a similar peak output, reaching approximately 113MW during the year.

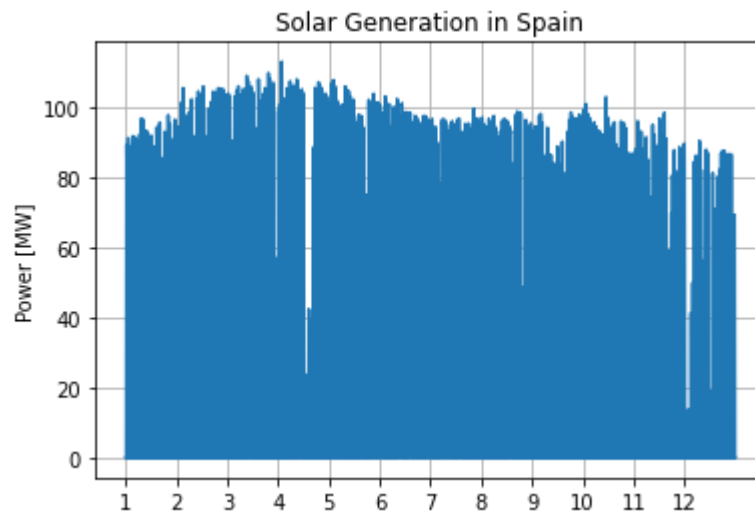


Figure 19. Solar Profile in Spain (2019)

The Spanish national grid is not as clean as its Swedish counterpart, despite having a substantial solar profile. In 2020, the carbon intensity in Spain was notably higher at 180gCO₂eq/kWh, approximately seven times greater than that of Sweden. Figure 20 from (Electricity Maps, 2022) provides further insights, indicating that Spain had 71% low-carbon technologies in its energy mix, with 46% of its electricity stemming from renewable sources.

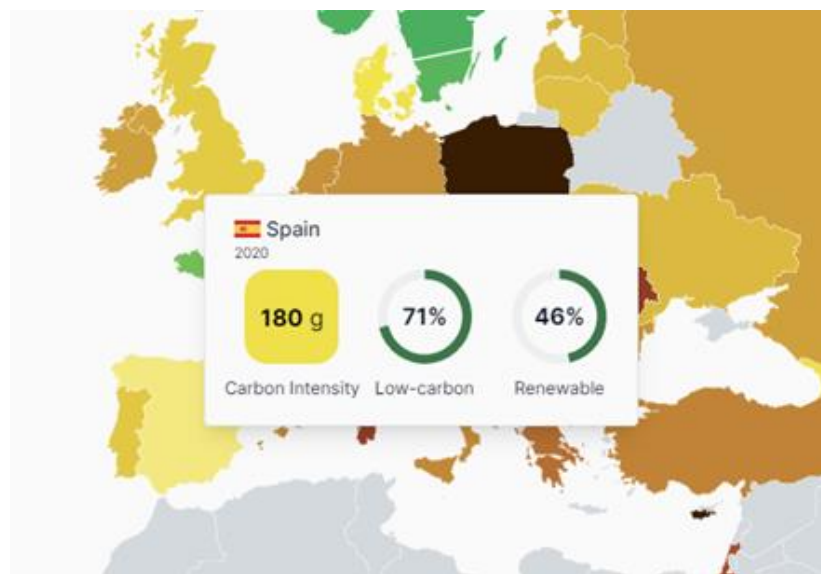


Figure 20. The national grid's aggregated carbon footprint for Spain in the year 2020 (Electricity Maps, 2022)

4.1.2 Scenarios

The inclusion of two study cases in this research offers a valuable opportunity to assess the impact of energy input and electricity prices on the cost-competitiveness and economic viability of such projects. However, it does not provide specific insights into which configurations or assets lead to improved LCOH, nor does it offer sufficient motivation for project developers to advance this technology. To address this, both study cases will be examined under four different scenarios. In the subsequent subchapters, these four scenarios will be elucidated, and mathematical formulations will be developed for each of them.

4.1.2.1 Scenario 1: Grid + PEM Electrolyzer

The first scenario presents a straightforward approach, with a direct connection of the PEM Electrolyzer plant to the grid. In this configuration, the dispatch optimization primarily hinges on electricity prices, focusing on hydrogen production during periods of low prices and ceasing production when prices are high. This scenario incurs the lowest CAPEX, as the main investment centers around the electrolyzer. Figure 21 visually represents this scenario, with the Grid_to_PEM behavior being the main variable to be determined by the optimization algorithm.

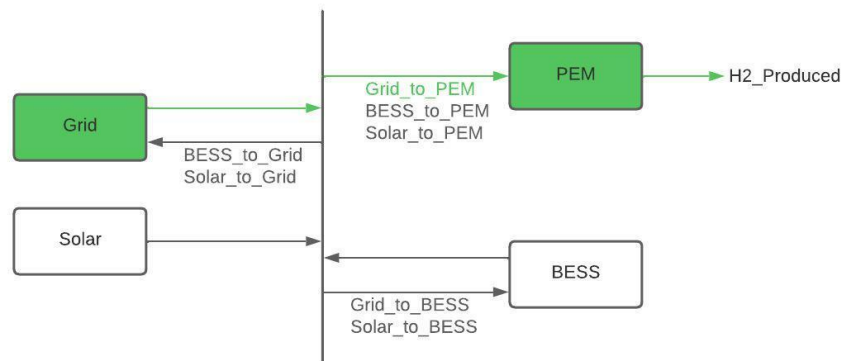


Figure 21. System Overview for Scenario 1

From an optimization perspective, the primary objective function is to maximize the net profit, which is obtained by calculating the difference between the total revenue and the overall costs. The optimization process is subject to three essential constraints. Firstly, the consumption of the electrolyzer must always remain below the grid input on an hourly basis. Secondly, the daily hydrogen production must exceed the hydrogen demand. While the system can generate surplus hydrogen for sale in the market, it should not produce less hydrogen than the pre-negotiated demand to maintain operational requirements. Lastly, the consumption of the electrolyzer should be lower than its installed capacity to ensure efficient utilization of the system. By satisfying these constraints, the optimization algorithm can determine the most economically viable and feasible dispatch strategy for the green hydrogen production system.

Mathematical Formulation:

$$\max(\text{Revenue} - \text{Costs})$$

subject to.

$$\text{GridtoPEM}[h] \leq \text{GridInput}[h]$$

$$\text{H2 Produced}[d] \geq \text{H2 Demand}[d]$$

$$\text{GridtoPEM}[h] \leq \text{Installed Capacity}$$

Equations:

$$\text{Revenue} = \text{sum}(\text{H2_Produced} * \text{H2_Price})$$

$$\text{Costs} = \text{sum}(\text{GridtoPEM} * \text{GridPPA})$$

4.1.2.2 Scenario 2: Scenario 1 + BESS

In the second scenario, we build upon the first one by introducing a battery system, resulting in an increase in CAPEX, but also a decrease in OPEX due to enhanced flexibility in avoiding consumption during periods of high electricity prices. With the integration of the battery system, the optimization algorithm would consider two additional variables: BESS_to_PEM and Grid_to_BESS. These variables respectively represent the discharging of the batteries and the charging of the batteries, with the condition that the batteries can only be charged via the grid and discharged through the PEM electrolyzer. Figure 22 illustrates the schematic representation of this scenario.

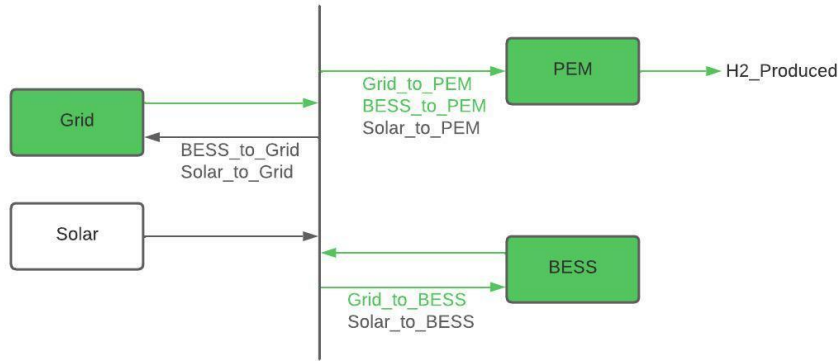


Figure 22. System Overview for Scenario 2

Likewise, the mathematical formulation is adjusted to accommodate the new asset. Four additional constraints are introduced. Firstly, constraints are imposed on the maximum charging and discharging rates to ensure that the variables representing the charging and discharging of the battery stay within these limits. Secondly, constraints are set on the maximum and minimum state of charge of the battery to ensure they remain within the defined bounds. In terms of costs, the total energy drawn from the grid would be determined by two variables: Grid_to_PEM and Grid_to_BESS, reflecting the energy supply to the PEM electrolyzer and the battery system, respectively.

Mathematical Formulation:

$$\begin{aligned}
 & \max(\text{Revenue} - \text{Costs}) \\
 & \text{subject to.} \\
 & \text{GridTOT}[h] \leq \text{GridInput}[h] \\
 & \text{H2 Produced}[d] \geq \text{H2 Demand}[d] \\
 & \text{GridtoPEM}[h] + \text{BESStoPEM}[h] \leq \text{Installed Capacity} \\
 & \text{GridtoBESS}[h] \leq \text{Max Charging Rate} \\
 & \text{BESStoPEM}[h] \leq \text{Max Discharging Rate} \\
 & \text{BESS SOC}[h] \leq \text{Max SOC} \\
 & \text{BESS SOC}[h] \geq \text{Min SOC} \\
 & \text{Equations:} \\
 & \text{Revenue} = \text{sum}(\text{H2}_{\text{produced}} * \text{H2}_{\text{Price}}) \\
 & \text{Costs} = \text{sum}(\text{GridTOT}[h] * \text{GridPPA}[h]) \\
 & \text{GridTOT}[h] = \text{GridtoPEM}[h] + \text{GridtoBESS}[h] \\
 & \text{ChargingPower}[h] = \text{GridtoBESS}[h] - \text{BESStoPEM}[h] \\
 & \text{BESS SOC}[h] = \text{BESS SOC}[h - 1] + \text{ChargingPower}[h] \\
 & \quad * (\text{BatteryEfficiency} / \text{BESS_Capacity})
 \end{aligned}$$

Moreover, an auxiliary variable named "Charging_Power" was introduced to indicate whether the battery system is charging or discharging, ensuring that only one of these processes occurs within each hour. In other words, the batteries cannot be simultaneously charged and discharged during the same time frame.

4.1.2.3 Scenario 3: Scenario 2 + Grid Injection

The third scenario, shown in Figure 23, introduces the option of grid injection, thus a new variable BESS_to_Grid, resulting in minimal changes to the CAPEX when compared to the previous scenario. However, the inclusion of this feature opens up an additional revenue stream, leading to improved OPEX prospects. The price at which the energy is injected back to the grid is equivalent to the prevailing electricity price.

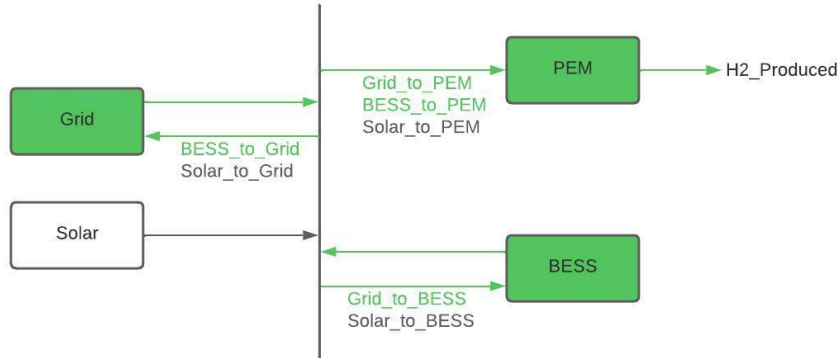


Figure 23. System Overview for Scenario 3

Regarding the mathematical formulation, the revenue calculation now incorporates the new variable "BESS_to_Grid." Furthermore, two additional constraints are introduced: the energy injected from the batteries to the grid must be greater than or equal to zero, while also being less than or equal to the maximum grid injection capacity. In this context, the maximum grid injection capacity refers to the power capacity of the grid connection line utilized in the project.

The auxiliary variable "Charging_Power" also takes into account that the battery's discharge can occur when the battery is injecting power back into the grid and/or supplying energy to the electrolyzer.

Mathematical Formulation:

$$\begin{aligned}
 & \max(\text{Revenue} - \text{Costs}) \\
 & \text{subject to.} \\
 & \text{GridTOT}[h] \leq \text{GridInput}[h] \\
 & \text{H2 Produced } [d] \geq \text{H2 Demand } [d] \\
 & \text{GridtoPEM}[h] + \text{BESStoPEM}[h] \leq \text{Installed Capacity} \\
 & \text{GridtoBESS } [h] \leq \text{Max Charging Rate} \\
 & \text{BESStoPEM}[h] + \text{BESStoGrid}[h] \leq \text{Max Discharging Rate} \\
 & \text{BESS SOC } [h] \leq \text{Max SOC} \\
 & \text{BESS SOC } [h] \geq \text{Min SOC} \\
 & \text{BESStoGrid } [h] \leq \text{Max Grid Injection} \\
 & \text{BESStoGrid } [h] \geq 0 \\
 & \text{Equations:} \\
 & \text{Revenue} = \text{sum}(\text{H2_Produced} * \text{H2_Price}) + \text{sum}(\text{BESStoGrid } [h] \\
 & \quad * \text{Price DayAhead } [h]) \\
 & \text{Costs} = \text{sum}(\text{GridTOT } [h] * \text{GridPPA } [h]) \\
 & \text{GridTOT } [h] = \text{GridtoPEM}[h] + \text{GridtoBESS}[h] \\
 & \text{ChargingPower } [h] \\
 & \quad = \text{GridtoBESS } [h] - (\text{BESStoPEM}[h] + \text{BESStoGrid}[h]) \\
 & \text{BESS SOC } [h] = \text{BESS SOC } [h - 1] + \text{ChargingPower } [h] \\
 & \quad * (\text{BatteryEfficiency}/\text{BESS_Capacity})
 \end{aligned}$$

4.1.2.4 Scenario 4: Scenario 3 + Solar Energy Input

Finally, the fourth scenario incorporates solar energy input as free electricity, as the impact of this asset on the economic context is mainly in the CAPEX. Once the solar panels are installed, the available energy is abundant. Consequently, this scenario is expected to have the lowest OPEX but the highest CAPEX. Additionally, three new variables are introduced to represent the flow of energy from the solar panels: Solar_to_PEM, Solar_to_BESS, and Solar_to_Grid. This scenario also presents the most complex optimal dispatch decision-making, as the algorithm must choose from various energy flows at each time step. Figure 24 illustrates the system overview with its corresponding variables.

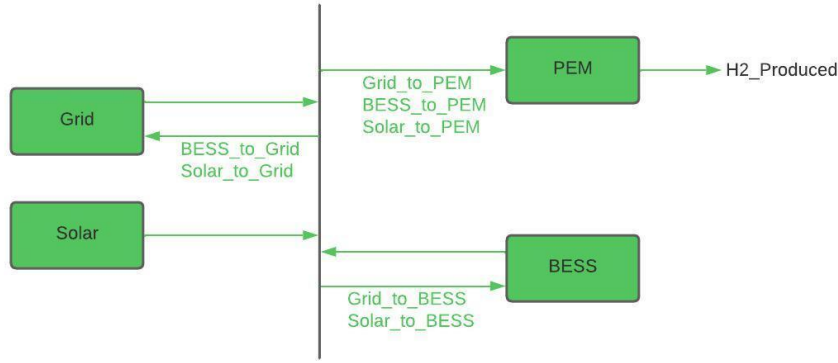


Figure 24. System Overview for Scenario 4

The introduction of these new variables introduces additional constraints in the mathematical formulation. Firstly, in the revenue calculation, the possibility of injecting energy back to the grid from the solar panels is taken into account. As for the charging power, the batteries can now be charged using the PV panels. Lastly, the energy consumed by the PEM Electrolyzer must consider the previously defined limits while accounting for the additional energy source from the solar panels.

Mathematical Formulation:

$$\max(\text{Revenue} - \text{Costs})$$

subject to.

$$\text{GridTOT}[h] \leq \text{GridInput}[h]$$

$$\text{H2 Produced}[d] \geq \text{H2 Demand}[d]$$

$$\text{GridtoPEM}[h] + \text{BESStoPEM}[h] + \text{SolartoPEM}[h] \leq \text{Installed Capacity}$$

$$\text{GridtoBESS}[h] + \text{SolartoBESS}[h] \leq \text{Max Charging Rate}$$

$$\text{BESStoPEM}[h] + \text{BESStoGrid}[h] \leq \text{Max Discharging Rate}$$

$$\text{BESS SOC}[h] \leq \text{Max SOC}$$

$$\text{BESS SOC}[h] \geq \text{Min SOC}$$

$$\text{BESStoGrid}[h] \leq \text{Max Grid Injection}$$

$$\text{BESStoGrid}[h] \geq 0$$

Equations:

$$\text{Revenue} = (\text{BESStoGrid}[h] + \text{SolartoGrid}[h]) * \text{Price DayAhead}[h]$$

$$\text{Costs} = \text{sum}(\text{GridTOT}[h] * \text{GridPPA}[h])$$

$$\text{GridTOT}[h] = \text{GridtoPEM}[h] + \text{GridtoBESS}[h]$$

$$\text{ChargingPower}[h] = (\text{GridtoBESS}[h] + \text{SolartoBESS}[h]) - (\text{BESStoPEM}[h] + \text{BESStoGrid}[h])$$

$$\text{BESS SOC}[h] = \text{BESS SOC}[h - 1] + \text{ChargingPower}[h] * (\text{BatteryEfficiency} / \text{BESS_Capacity})$$

4.1.3 System Configuration

4.1.3.1 BESS – Solar PV - Grid

The battery system was modelled considering the proposed AC-coupled PV-plus-battery configuration from (NREL, 2023), as illustrated in Figure 25. The study compared this configuration with the DC-coupled PV-plus battery one, stating benefits and drawbacks from both configurations. The AC option was selected for this study due to the maturity of this solution, backed by the research in (Gallardo *et al.*, 2022).

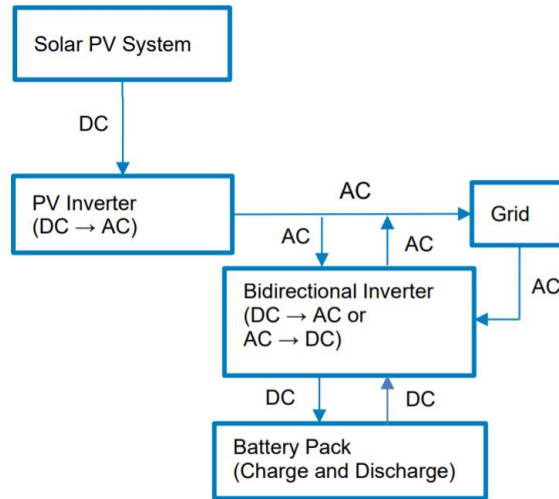


Figure 25. Components of an AC-coupled PV-plus-battery system (NREL, 2023)

4.1.3.2 PEM Electrolyzer

The PEM Electrolyzer model used was based on the electrolyzer models from top commercial providers worldwide from (Southern Lights, 2023). Figure 26 offers an overview of the specific energy consumption (SEC) of a PEM Electrolyzer. Nonetheless, due to the selected MILP optimization selected, and considering the non-linearity of the SEC curve, it is assumed that the specific energy consumption is constant, with a value of 59kWh/kgH₂.

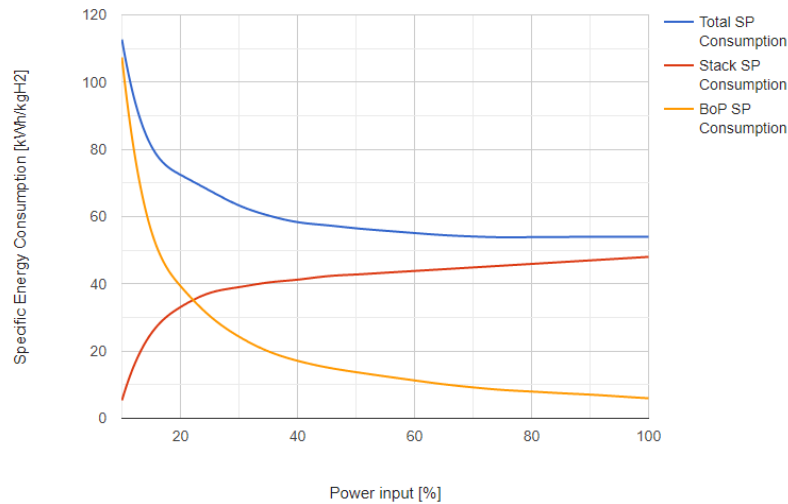


Figure 26. Specific Energy Consumption of PEM Electrolyzer (Southern Lights, 2023)

As outlined in the work by (Gallardo et al., 2021), they suggest that although the electrolyzers could potentially experience overload for brief intervals of up to 160% of the installed capacity, this aspect is disregarded due to the hourly timestep exceeding the load threshold timeframe of 10 to 30 minutes. Similarly, this argument also permits the omission of the electrolyzer's dynamic response (e.g. ramp-up, ramp-down, etc.) since it can transition from 0 to 100% operation within an hour.

4.1.3.3 Economic and Financial Parameters

Given the substantial initial capital required and the extended duration for achieving a favorable return on investment, the project financing framework envisions a lifetime of 20 years, guided by a Weighted Average Cost of Capital (WACC) set at 8%, as per the default value stipulated by (IEA, 2019). Some assets will require a new investment after some years due to degradation (as LiB and PEM's stacks).

Table 5 presents the costs encompassing the assumptions listed above for project finance and both capital expenditures (CAPEX) and operational expenditures (OPEX) attributed to the entire system. The figures within this table are derived from multiple sources, including (Mongird et al., 2020; Gallardo et al., 2022; NREL, 2023).

Cost	Item	Value	Unit
CAPEX	PV Modules	0.4	USD/Wdc
	Solar BoP	0.1	USD/Wdc
	Solar Development (cost & margin)	0.1	USD/Wdc
	Grid-forming inverter	0.07	USD/Wac
	Electrolysis PEM Plant	1.2	USD/Wac
	PEM Development (cost & margin)	0.5	USD/Wac
	LI-Ion Battery (cost & margin)	0.395	USD/Wh
OPEX	O&M Solar	0.04	USD/Wdc-year
	O&M Electrolyzer	0.024	USD/Wac-year
	O&M BESS	0.001	USD/Whc-year
	Tap water cost	2	USD/m3
Financial assumptions	WACC	8	%
	Lifetime	20	years

Table 5. Economic parameters and financial assumptions (Mongird et al., 2020; Gallardo et al., 2022; NREL, 2023, IEA, 2019)

4.1.3.4 Sizing Assets

In formulating the technical specifications for the system components, a review of commercially ready technologies implemented in projects similar to the one described in this study were assessed. The system's design is geared toward achieving the following objectives:

1. Drawing energy from the grid to meet the installed capacity requirements of the PEM electrolyzer and facilitate the charging of the BESS.
2. Ensuring that the PEM-BESS subsystem can operate autonomously, acting as a standalone unit for an extended period of approximately 3-4 hours, without depending on solar or grid inputs.
3. Capitalizing on the solar plant's capacity to provide "cost-free" energy, as it constitutes an asset with a substantial impact on CAPEX while exerting a comparatively minor influence on OPEX. The peak generation should be able to meet the PEM rated capacity and provide a surplus that can be utilized to either charge the BESS or inject back to the grid.

When considering the dimensioning of system components, the limitations of the grid connection are not constrained by existing commercial technologies, as there exist various cables and protections capable of accommodating the proposed system. Additionally, the adaptable nature of both the PEM electrolyzer and the Solar PV system allows for flexibility in design, permitting the addition of necessary capacity to fulfill the overall system demands. For this reason, the sizing methodology was initiated with the BESS, as this technology is subject to the developments in large-scale battery manufacturing.

As explored in the BESS section, (NREL, 2023) presents a utility-scale PV-Plus-Battery configuration that ensures a harmonious interplay between these two subsystems in line with industry requisites. Consequently, the system incorporates Solar PV panels capable of achieving a peak generation of 130MW, along with a Li-Ion battery boasting a 240MWh capacity and a discharging rate of 60MW.

Subsequently, the PEM Electrolyzer's installed capacity is determined at 100MW, aligning with the considerations outlined in points 2 and 3 above. Ultimately, the sizing of the grid connection is derived from the maximum feasible energy input required to fulfill point 1, thus combining the PEM's rated capacity with the battery's charging rate. Figure 27 shows the system with the component's main characteristics.

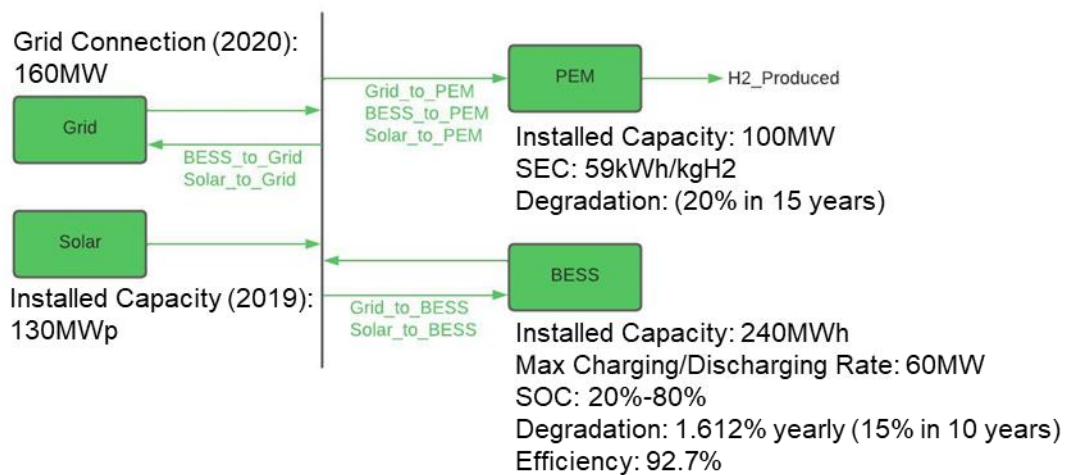


Figure 27. System overview with component's main characteristics

4.2 Key Performance Indicators

To determine the economic viability of projects, it is crucial to carefully evaluate various key performance indicators (KPIs) that shed light on different aspects of the project's financial outlook. Among the four essential indicators analyzed in this study, capital expenditure (CAPEX) provides insights into the initial investment required for setting up the infrastructure and equipment. Operating expenditure (OPEX) presents the ongoing costs incurred during the operation and maintenance of the project. These two indicators, together, offer a comprehensive understanding of the financial commitment involved in the project's life cycle.

Moreover, the levelized cost of hydrogen (LCOH) is a critical KPI that considers both CAPEX and OPEX, providing a unified metric to assess the average cost of producing hydrogen over the project's lifetime. By factoring in the total costs and the projected amount of hydrogen produced, LCOH enables decision-makers to gauge the project's cost-effectiveness compared to alternative

hydrogen production methods. Lastly, net profit highlights the financial gains or losses incurred after deducting all expenses from the project's revenue. This indicator offers a clear picture of the project's financial viability, indicating whether it can generate sustainable profits over time.

By carefully evaluating these key performance indicators, project stakeholders can make informed decisions about the economic feasibility of green hydrogen projects. The combination of CAPEX, OPEX, LCOH, and net profit analysis provides a robust framework to assess potential risks and returns, aiding in the identification of economically viable projects that align with sustainable business objectives. This comprehensive approach ensures that project development proceeds with a thorough understanding of the financial implications, fostering a more sustainable and economically sound future for green hydrogen production:

4.2.1 CAPEX

The capital expenditures (CAPEX) in a large-scale renewable energy project encompass the significant one-time expenses incurred during the project's inception, typically involving substantial amounts of capital. These expenses not only cover the initial investment but also account for replacement costs over the project's entire lifespan.

The CAPEX for a large-scale renewable energy project includes a variety of essential expenditures, such as the costs associated with acquiring and installing renewable energy infrastructure, such as solar panels, wind turbines, or other renewable energy generators. Additionally, it considers expenses related to the construction of supporting infrastructure, such as transmission lines, substations, and energy storage systems, necessary for the efficient integration and operation of the renewable energy facilities.

Furthermore, CAPEX may also encompass expenses associated with obtaining permits, conducting environmental impact assessments, and engaging in engineering and design work. It is crucial to carefully evaluate these capital expenditures, as they significantly influence the project's overall economics and its ability to deliver sustainable and cost-effective energy solutions.

4.2.2 OPEX

Operational expenditures (OPEX) constitute the ongoing and recurrent expenses necessary to maintain the continuous operation and functionality of a project, and they hold particular significance in the context of large-scale renewable energy projects. These expenses encompass a wide range of operational costs that are vital for the functioning of the renewable energy facilities throughout their operational life.

In the case of large-scale renewable energy projects, OPEX includes various critical elements. One significant aspect is the cost of labor, encompassing

salaries and wages for the workforce responsible for the operation, maintenance, and management of the renewable energy infrastructure. Skilled personnel are essential to ensure the optimal performance, safety, and reliability of the energy facilities.

Moreover, OPEX covers expenses related to utilities and services required for the operation of the renewable energy project. These include costs for electricity, water, and other essential utilities needed to support day-to-day operations. Additionally, expenditures for routine maintenance, repair work, and periodic inspections are essential to uphold the longevity and efficiency of the renewable energy assets.

Furthermore, OPEX also extends to other recurring costs, such as insurance premiums, regulatory compliance fees, and any expenses associated with environmental monitoring and reporting. Proper management and control of operational expenditures are crucial to maintain the economic viability of large-scale renewable energy projects, ensuring that they remain financially sustainable and continue to deliver clean and reliable energy to the grid and end-users.

An efficient OPEX management approach enhances the overall project performance and contributes to the long-term success and competitiveness of large-scale renewable energy endeavors. Dispatch plays a key role in achieving high-performance levels and achieving more cost-competitive results for these innovative solutions.

4.2.3 Levelized Cost of Hydrogen (LCOH)

The Levelized Cost of Hydrogen (LCOH) is a widely recognized metric used to evaluate the economic viability of hydrogen-based projects. It is measured in USD or EUR per kilogram of H₂, representing the cost per unit of hydrogen mass. Essentially, it represents a fictitious price at which the project developer would need to charge for each unit of hydrogen produced over the entire project's lifetime to break even without making any profit.

From the perspective of the project developer, it is essential to consider that the market price of hydrogen is not solely determined by the LCOH. In this context, a lower value of LCOH would be highly desirable, as it would imply a lower cost of hydrogen production. This means that the project developer would have the flexibility to sell their hydrogen at a competitive price, potentially capturing a larger market share and achieving profitability beyond breakeven.

The LCOH formula is displayed in Equation 1. The numerator of the equation encompasses all project costs throughout its lifetime, while the denominator represents the total hydrogen production over the project's lifespan. The equation does not consider the decommissioning of the power plant at the end of its lifetime.

$$LCOH = \frac{\sum_{n=1}^N \frac{CAPEX_n + OPEX_n}{(1+r)^n}}{\sum_{n=1}^N \frac{HydrogenProduction_n}{(1+r)^n}}$$

Equation 1. Determines the Levelized Cost of Hydrogen considering the CAPEX, OPEX, Hydrogen Production, Return Rate and Lifetime of the Project

Despite hydrogen production being a constant physical quantity that does not depreciate over time – as 1kg of hydrogen today remains equivalent to 1kg in 10 years – its economic value changes over time. This is a result of the mathematical formulation involving the discounting of annual revenue streams. Essentially, it can be observed as if the economic value of that kilogram of hydrogen changes both today and in the context of a 10-year span.

4.2.4 Net Profit

Net profit is a crucial financial metric that reveals the remaining money after deducting all business-related operational costs. In the context of this project, the net profit is calculated by subtracting the production costs from the revenues generated.

When assessing the net profit on an hourly basis for the dispatch optimization, two primary revenue streams are considered: hydrogen produced and energy injected into the grid. These revenues are evaluated on an hourly timeframe to gain insights into the project's financial performance throughout the day.

On the expense side, the only hourly cost considered is the electricity purchased from the grid. Although there are additional expenses associated with the system's operation, such as maintenance costs and other operational expenditures, these are taken into account at an aggregated level on a yearly basis. For the purpose of determining the optimal hourly dispatch, the focus remains on the three key components listed in this subchapter: hydrogen production, energy injected to the grid, and the cost of grid electricity. This approach provides a more granular view of the project's financial performance, allowing for strategic decision-making to maximize net profit and overall project profitability.

4.2.5 CO₂ Emissions

Figure 28, sourced from (Tenhumberg and B  ker, 2020), provides a visual representation of the carbon emissions associated with water electrolysis as a function of the carbon footprint of the electricity grid supplying the energy. From this illustration, it becomes evident that the magnitude of the electricity grid's carbon emissions significantly impacts the resulting carbon footprint attributed to hydrogen production, regardless of the technology employed.

In order to gauge the emissions associated with water electrolysis, a reference point is established by comparing it to the carbon footprint of hydrogen production via Steam Methane Reforming (SMR). When the electricity generation mix of an electrical grid is already characterized by a high level of carbon intensity, opting for SMR may prove to be a more environmentally favorable choice for hydrogen production as opposed to water electrolysis.

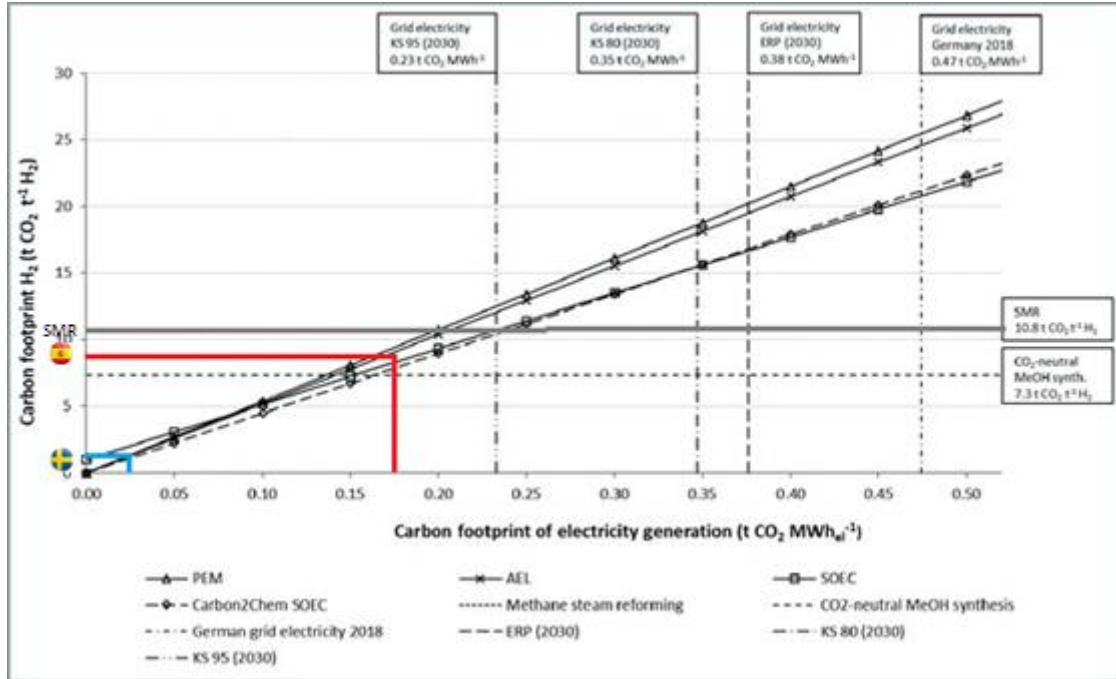


Figure 28. Carbon footprint of hydrogen with respect to the carbon footprint of the supplying electricity grid

For enhanced specificity, Figure 28 has been adapted to delineate the carbon footprint originating from the Swedish and Spanish electricity grids, quantified as 1 ton of CO₂ per ton of hydrogen for Sweden and 8 tons of CO₂ per ton of hydrogen for Spain. These values will be taken into consideration in the upcoming results chapter, facilitating an evaluation of the environmental performance of this solution, especially when incorporating a renewable energy source like solar power.

4.3 Optimization Algorithm

Figure 29 provides an overview of the flowchart employed in this study, spanning from initial input data to the ultimate outcomes achieved during post-processing of optimization results. The design of the flowchart was based on the work of (Marocco *et al.*, 2021; Trevisan, Buchbjerg and Guedez, 2022). The entire model was constructed using Python scripts, using well-established libraries like NumPy and Pandas, as well as more specialized tools such as Pyomo with the Gurobi solver for optimization.

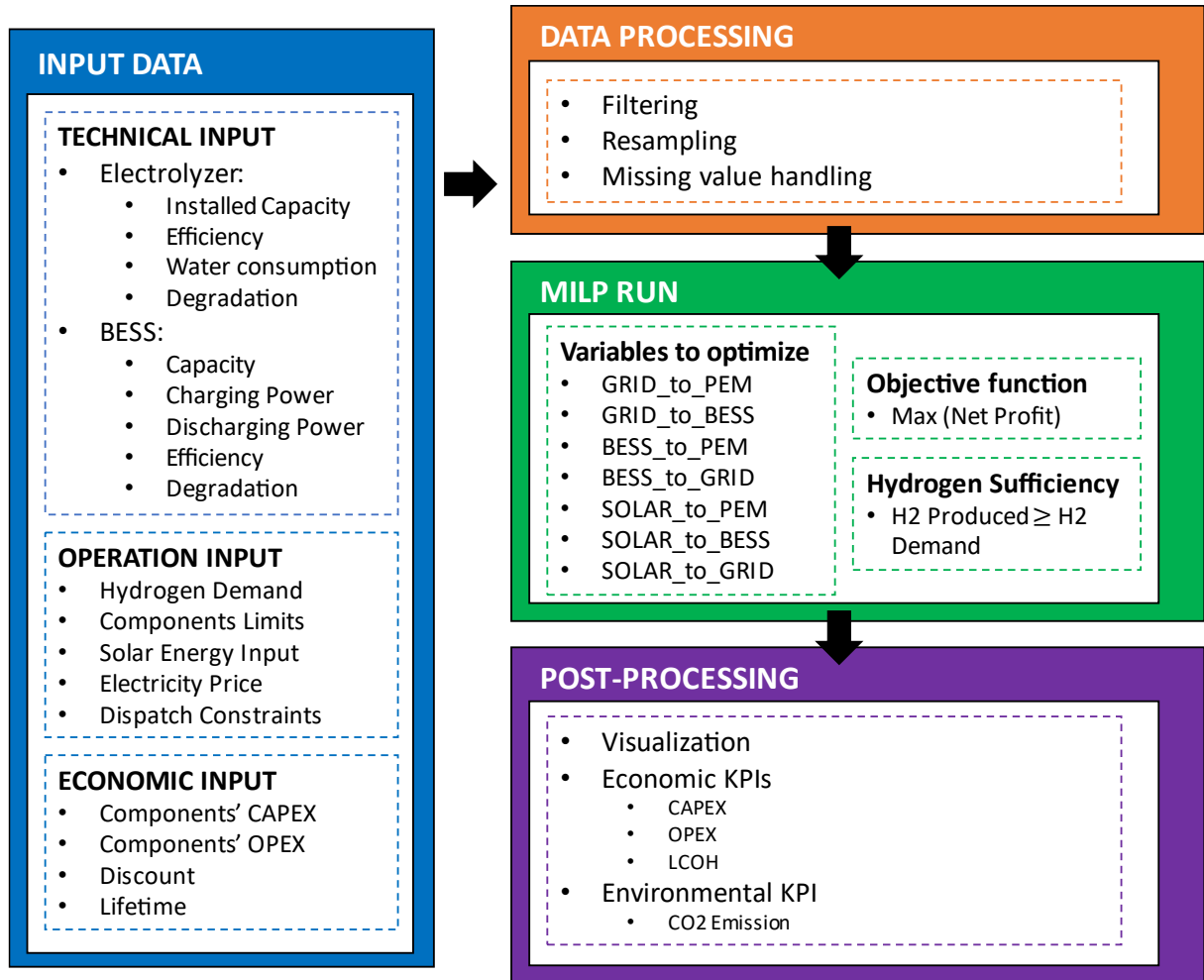


Figure 29. Flowchart describing the sequence of methods by means of the MILP technique

Commencing the flowchart is the data input stage. Technical inputs were presented in subsection 4.1. While the thesis doesn't delve into data management techniques, essential criteria necessitated that the data be structured in an hourly basis over a full year. For the piecewise affine approximation, the algorithm is responsible for linearizing the nonlinear operational curve of the PEM electrolyzer, enabling its solution through MILP solvers.

The third element in the flowchart is optimization, where the objective function is the net profit at every hour, ensuring a daily hydrogen sufficiency where hydrogen production exceeds or equals demand. The variables subject to optimization consist of the different energy flows across the system.

Lastly, the post-processing stage refines the results, generating graphs that facilitate drawing conclusions and understanding the actual behavior of the system over the year. Additionally, economic KPI calculations help determine whether the system, across its two study cases and four scenarios, yield feasible projects or if the current technologies, along with their associated costs, policies and market dynamics and not yet conducive to large-scale implementations of this nature.

4.4 Sensitivity Analysis

The optimal dispatch of the system is influenced by a multitude of factors, and altering these factors can lead to varying system behaviors and conclusions. To ensure the impartiality of our study and to explore the full spectrum of potential outcomes, we conducted a sensitivity analysis. In this analysis, we focused on two primary parameters that have the most significant impact on the results across the four distinct scenarios and the two selected study cases.

Through iterative experimentation with various technical and operational inputs, it became evident that the two parameters wielding the most influence were the price of hydrogen (H_2 price) and the capacity of the Battery Energy Storage System (BESS). The H_2 price plays a pivotal role in the algorithm's decision-making process, as it determines whether hydrogen production is financially viable at a given time and to what extent. On the other hand, the BESS is the asset among the existing in the system which provides the largest flexibility, by facilitating the dynamic flow of energy in response to electricity price fluctuations and solar resource availability.

To set the baseline for our analysis, we established the H_2 price at \$2 per kilogram. This figure aligns with projections from multiple reports (BloombergNEF, 2020; Hydrogen Council, 2023; IEA, 2023), indicating its appropriateness for the hydrogen market in both of our selected countries over the next two decades. As for the BESS capacity, our initial value was determined through the review of commercially available battery technologies (NREL, 2023). In order to visualize the potential shifts brought about by the sensitivity analysis, we chose to explore variations of +/- \$1 per kilogram for the H_2 price and +/- 120 MWh for the BESS Capacity. In simpler terms, this means assessing scenarios in which the batteries can sustain the system for 2, 4 (baseline), or 6 hours independently.

4.5 Testing Framework

There are 60 cases across the different scenarios, countries and sensitivities. Figure 30 presents a testing framework of the different cases and is used to provide clarity regarding what study case is being analyzed during the results section. The reason why scenario 1 doesn't consider variation in the BESS capacity is because in this particular scenario the system doesn't contemplate storage.

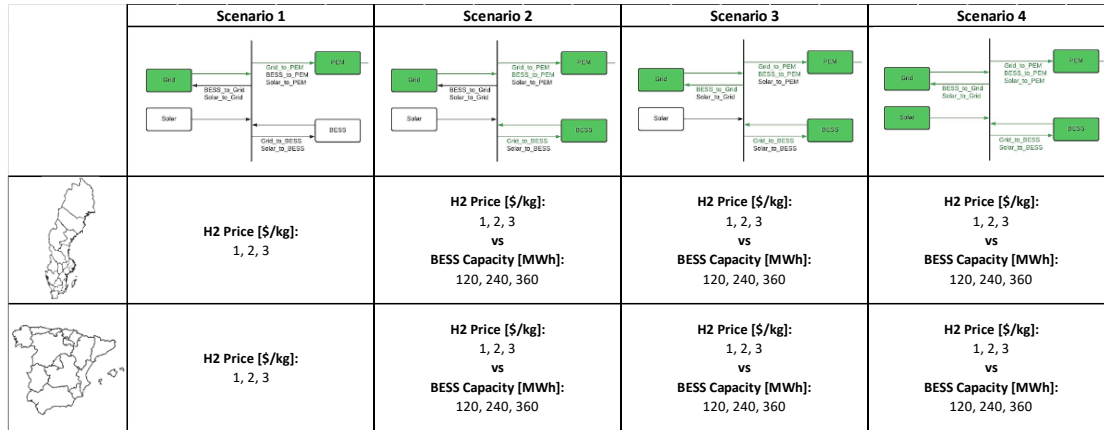


Figure 30. Testing Framework of the study considering the four scenarios, the two countries and the sensitivity analysis

From each of these cases, nine results are being stored to conclude the behavior of the system. The results or metrics are:

- LCOH (Levelized Cost of Hydrogen)
- NPV (Net Present Value) of the Net Profit
- NPV of the CAPEX
- NPV of the OPEX
- Total Hydrogen Produced
- CO₂ Emissions
- CO₂ Emissions SMR

From this metric, five tests will be studied comparing scenarios and/or countries.

4.5.1 Tests Performed

Test 1: Sensitivity Analysis: BESS Capacity vs H₂ Price

- Scenario 1 vs Scenario 2 vs Scenario 3 vs Scenario 4 – Sweden
- Scenario 1 vs Scenario 2 vs Scenario 3 vs Scenario 4 – Spain

Test 2: Multi-Energy System Dispatch Behavior

- Scenario 4: Sweden
- Scenario 4: Spain

Test 3: Electricity Price vs Solar Availability

- Scenario 4: Sweden vs Spain

Test 4: Economic KPIs

- Scenario 1 vs Scenario 2 vs Scenario 3 vs Scenario 4: Sweden
- Scenario 1 vs Scenario 2 vs Scenario 3 vs Scenario 4: Spain

Test 5: CO₂ Emissions

- Scenario 3 vs Scenario 4: Sweden
- Scenario 3 vs Scenario 4: Spain

5 Results & Analysis

5.1 Sensitivity Analysis: BESS Capacity vs H₂ Price

In Figure 31, the results of the sensitivity analysis are depicted across all scenarios and countries, shedding light on key findings crucial for understanding the economic viability of the proposed projects.

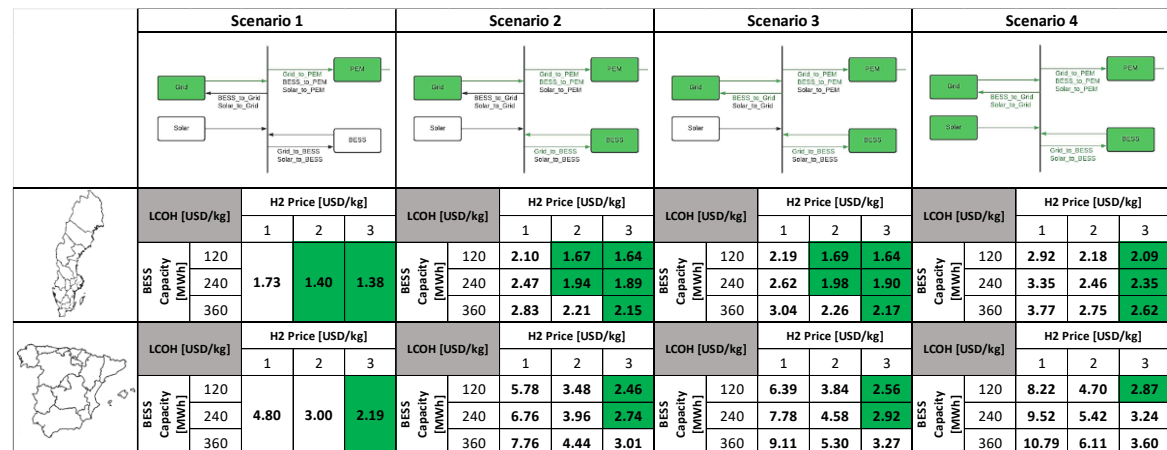


Figure 31. LCOH results from the Sensitivity Analysis

First, the optimal configuration for these large-scale projects emerges with resounding clarity—a BESS capacity of 120MWh and a hydrogen price of 3 USD/kgH₂. This combination stands as the optimal for achieving cost-competitive and economically feasible green hydrogen production.

Conversely, a stark revelation from this analysis is that when the hydrogen price is reduced to 1 USD/kgH₂, the project becomes non economically feasible. This underscores the extreme sensitivity of the projects to the H₂ price, emphasizing the need for a stable and favorable hydrogen market to foster their success.

Moreover, it is imperative to note that Scenario 3 and 4 introduce an additional revenue stream (injecting back to the grid) beyond what is typically represented by the Levelized Cost of Hydrogen (LCOH). This highlights the multifaceted nature of project economics and the need to consider all potential income sources when evaluating feasibility. The concept of LCOH doesn't represent a trustworthy metric when evaluating these type of projects.

Notably, the Swedish scenario stands out due to its exceptionally low electricity prices, serving to foster the development of these projects. This reaffirms the notion that local market conditions play a pivotal role in determining the economic attractiveness of green hydrogen initiatives.

5.2 Multi-Energy System Dispatch Behavior

Figure 32 provides a detailed time-series analysis of the PEM Electrolyzer's performance in Sweden during both the summer and winter solstices, specifically focusing on Scenario 4. These solstices serve as extreme cases, representing the longest and shortest daylight periods of the year, and offer valuable insights into the system's behavior. The time frame showed is three days or 72 hours. The graph is divided into three distinct sections. The upper portion illustrates the three primary energy inputs that supply the PEM Electrolyzer: BESS (in blue), Solar (in orange), and Grid (in green). While it is not possible to visually observe all energy flows due to operational constraints (such as the inability to discharge while charging and vice versa, or the inability to inject back into the grid while consuming), we can infer their behavior based on the actions of the visible flows.

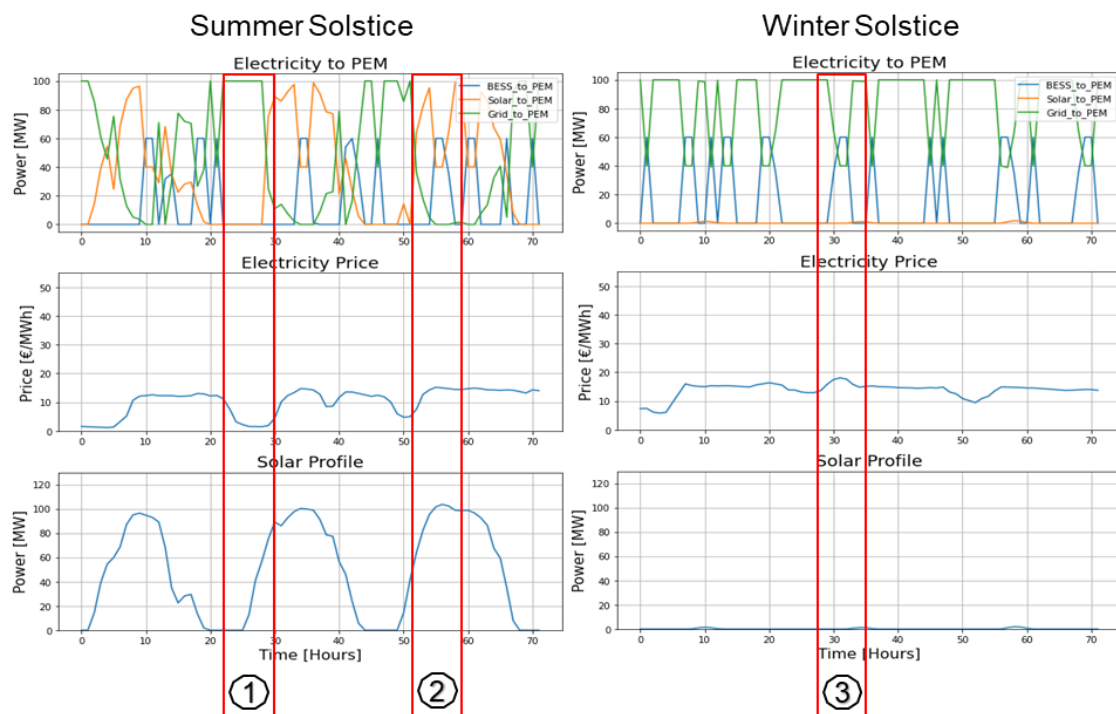


Figure 32. Timeseries behavior of the PEM Electrolyzer in Sweden during summer and winter solstices

The middle section depicts the corresponding electricity prices, which fluctuate between 2USD/MWh and 18USD/MWh, a crucial factor to consider when comparing the behavior with the Spanish case. Finally, the lower part of the graph showcases solar power generation. During the summer, solar output peaks at 100MW, matching the installed capacity of the PEM Electrolyzer, while during the winter, it drops significantly to around 2MW, a negligible amount.

Examining the three selected moments over the course of these three days offers valuable insights into system dynamics.

- 1 Characterized by low energy prices and increasing solar production, the system optimally relies on grid supply for 100% of hydrogen production while gradually reducing overall consumption to prioritize solar energy utilization.
- 2 Marked by high electricity prices and abundant solar generation, the PEM Electrolyzer draws power from the Battery Energy Storage System (BESS), while the surplus solar energy is redirected to the grid.
- 3 Where solar energy is entirely absent, the system engages in price arbitrage. During peak pricing hours, energy is supplied by the storage system to fuel the electrolyzer, while during off-peak periods, the grid provides energy to the electrolyzer while simultaneously recharging the batteries.

Figure 33 provides a comprehensive time-series analysis of the PEM Electrolyzer's operation in Spain, encompassing both summer and winter solstices. This dual perspective illustrates how the system responds to varying solar and price conditions.

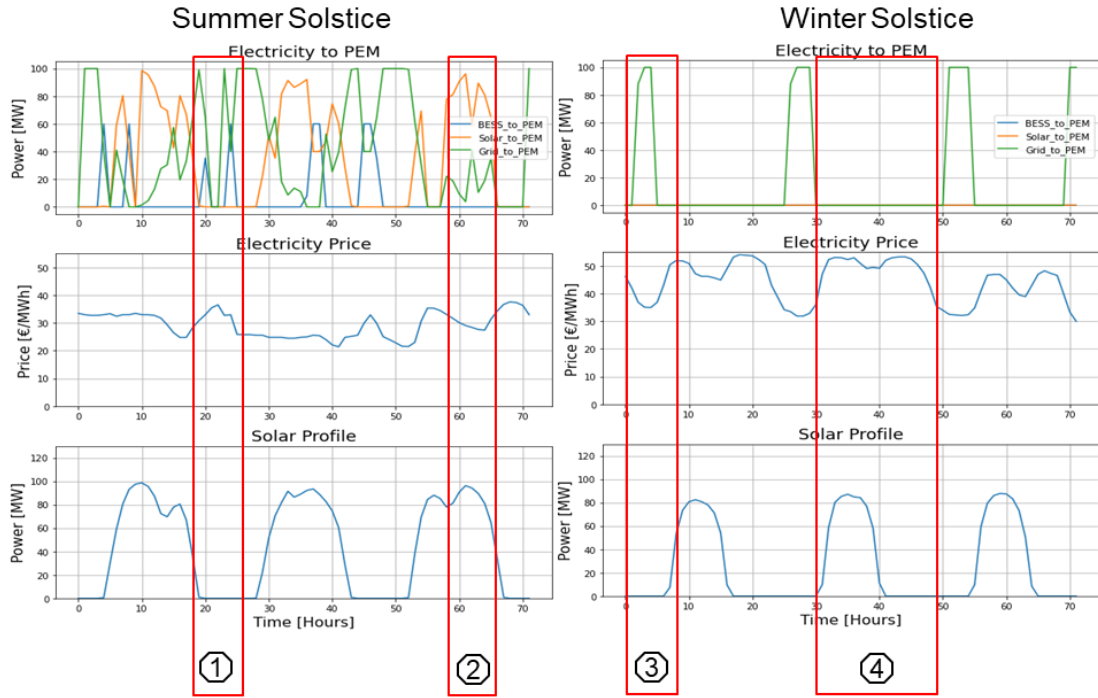


Figure 33. Timeseries behavior of the PEM Electrolyzer in Spain during summer and winter solstices

Four moments have been selected to explain the algorithm's decision-making.

- 1 During periods characterized by high electricity prices and minimal solar production, the electrolyzer strategically reduces its output to zero. This adaptability is crucial for cost-efficiency when grid electricity is costly.
- 2 As solar production reaches its peak, the electrolyzer seizes the opportunity to harness abundant solar energy. It primarily draws power from solar input, with any surplus energy being stored within the batteries for future use. This flexible operation optimizes resource utilization.

- 3 The system demonstrates how the hydrogen output is reduced to its minimum to meet the 24-hour demand constraint. It only operates during times of the lowest electricity prices. Consequently, storage is largely neglected in the operation during winter months.
- 4 In this configuration, the entirety of solar generation is directed toward grid injection. This choice is motivated by the presence of high electricity prices. The system remains unchanged in this mode, even when electricity prices exhibit small fluctuations above 40 USD/MWh.

By examining these four distinct moments, we gain a comprehensive understanding of how the system adapts to diverse scenarios in Spain, shedding light on its operational flexibility and responsiveness to market conditions.

Additionally, these graphs offer valuable insights into the system's adaptability and cost-saving strategies during varying conditions, however, it doesn't show on an aggregated level how the system used its different assets. Figure 34 and 35 show the Sankey diagrams of both countries respectively.

Sankey diagrams are powerful visual tools that allow us to gain a comprehensive understanding of how energy flows within a system. These diagrams provide a clear representation of the distribution and transformation of energy throughout different components of a system. In essence, Sankey diagrams display the input and output of energy in a way that makes it easy to see where energy is being utilized or lost. By using varying widths of arrows, they depict the proportion of energy that flows through each pathway, providing a visual summary of energy utilization.

In the context of this study, Sankey diagrams were utilized to shed light on how the renewable energy system operates in Sweden and Spain over the course of a year. These diagrams present an aggregated view of how the system allocates its energy resources across various components. In Figure 34, which represents the Swedish case, it is shown that the majority of solar input is channeled into feeding the PEM electrolyzer. The BESS serves as a buffer during periods of high electricity prices, with most of the stored energy later utilized for hydrogen production. This observation leads us to conclude that the system places a strong emphasis on profitable hydrogen generation, which becomes a priority throughout its annual operation.

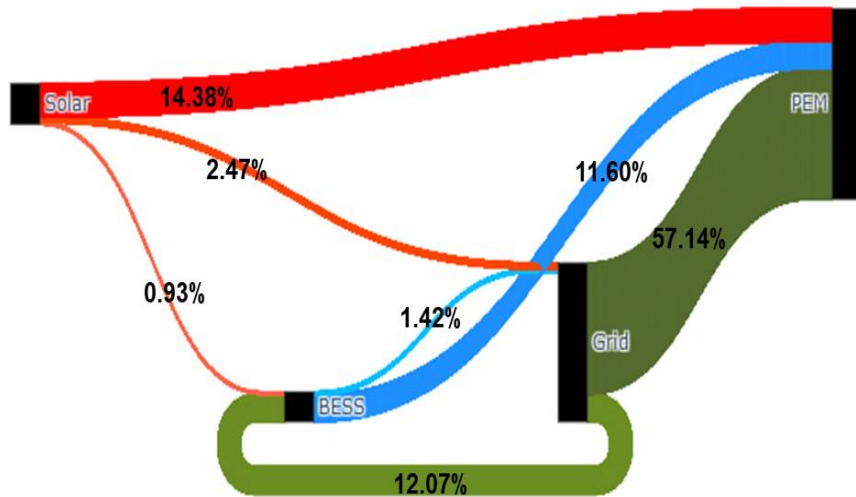


Figure 34. Sankey Diagram on the energy flows for Sweden in the Scenario 4

Conversely, Figure 35, representing the Spanish case, reveals a distinct pattern. Here, solar production is divided into two significant outputs: one directed towards hydrogen production and the other towards grid injection. Notably, the energy stored from the grid is similar to the one injected back into the grid from the storage system. In the Spanish context, where electricity prices tend to be higher, the system's operation leans towards economic optimization through price arbitrage. This strategy involves leveraging the differences in electricity prices to maximize revenue by injecting surplus energy back into the grid, all while consistently meeting the hydrogen demand constraint.

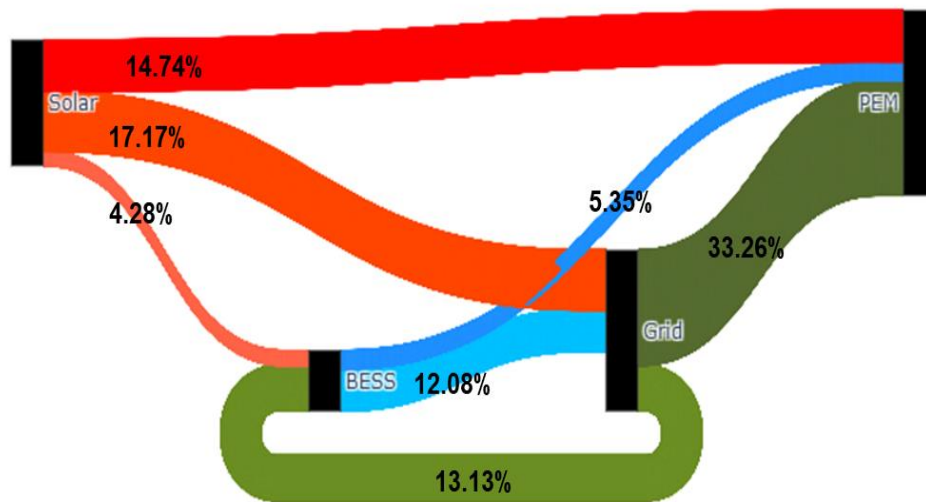


Figure 35. Sankey Diagram on the energy flows for Spain in the Scenario 4

These Sankey diagrams provide valuable insights into how the renewable energy system adapts to varying conditions and employs cost-saving strategies. They offer a visual representation of the complex interplay of energy within the system, helping us draw conclusions about its behavior and priorities.

5.3 Electricity Price vs Solar Availability

In the third test within the results section, the focus shifts to a monthly comparison within Scenario 4. This analysis reviews the percentage of power used by the PEM Electrolyzer from various sources – the grid, BESS, and solar, along with the total hydrogen production attributed to these sources. Figure 36 provides visual representation, where the upper part of the figure pertains to the Swedish case, and the lower part to the Spanish one. On the left side, the graph illustrates the breakdown of power consumption by source, while the right side delves into the corresponding hydrogen production. The color scheme assists in distinguishing between the sources: blue for the grid, orange for solar, and green for BESS.

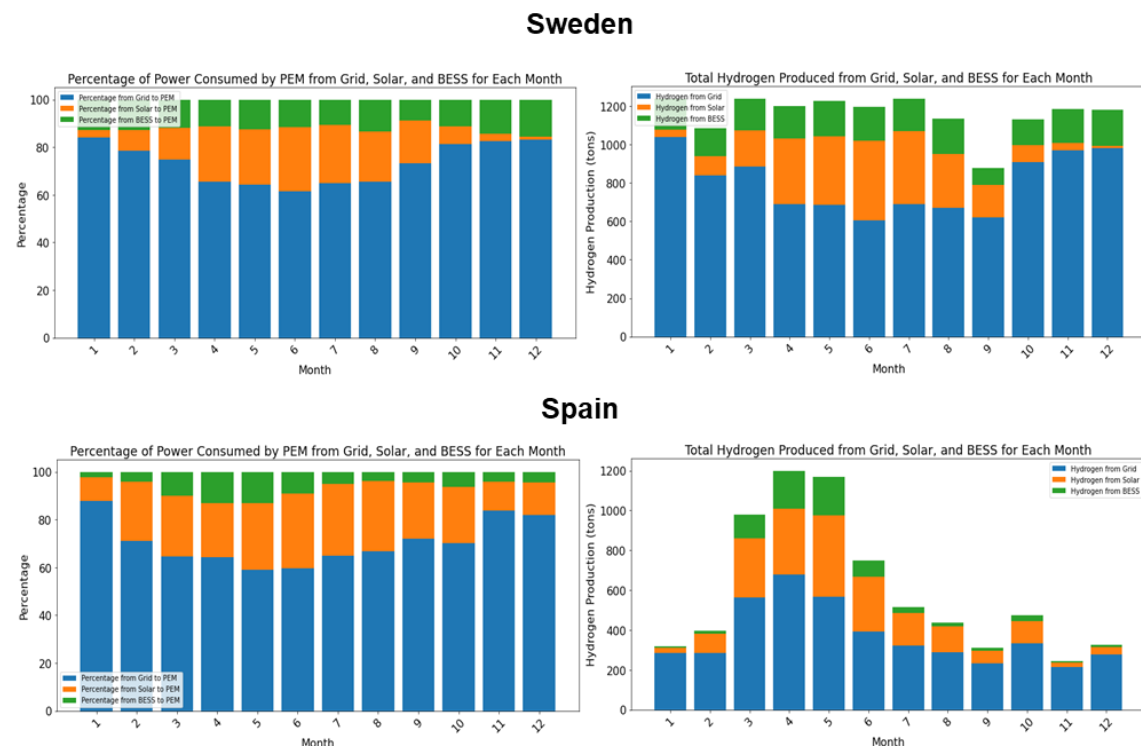


Figure 36. Monthly Variations in PEM Electrolyzer Operation and Hydrogen Production for Sweden and Spain

Figure 36 reveals that the pivotal factor influencing dispatch algorithm decisions is the electricity price. In the Spanish context, particularly during the winter months, a preference for injecting excess power back into the grid is evident. This choice results in a notable reduction in hydrogen production, typically amounting to approximately one-third when compared to the system's peak performance months, such as April and May. Conversely, this behavior is not mirrored in the Swedish case, where hydrogen production remains consistently high for 11 out of the 12 months in the year.

Furthermore, the data from the entire year underscores the consistent utilization of energy storage in Sweden. In contrast, Spain significantly curtails its energy storage operation during the winter months. This adjustment is primarily driven by the utilization of solar input to fulfill the minimum

hydrogen demand, with any surplus being injected back into the grid instead of being stored. Conversely, the Swedish system diminishes its reliance on solar input during the winter period due to its limited power output during this season.

5.4 Economic KPIs

In the context of the fourth section, the fourth assessment within the testing framework pertains to economic indicators across the four scenarios. This evaluation considers a hydrogen price of 3 USD per kilogram and a storage capacity of 120 megawatt-hours, which represents the lowest capacity within our sensitivity analysis. Remarkably, this specific combination emerged as the most favorable scenario for the studied system, as elaborated upon in the initial section of the results chapter.

Figure 37 illustrates the Net Present Value (NPV) metrics, specifically NPV Net Profit (depicted in blue), NPV Capex (depicted in orange), and NPV Opex (depicted in green), across all four scenarios for both Sweden (upper section) and Spain (lower section). The black dashed line serves as a reference point denoting the highest NPV Net Profit among all scenarios. These values reflect the cash flow converted to present value terms, utilizing a Weighted Average Cost of Capital (WACC) of 8% and a discounted project lifetime of 20 years.

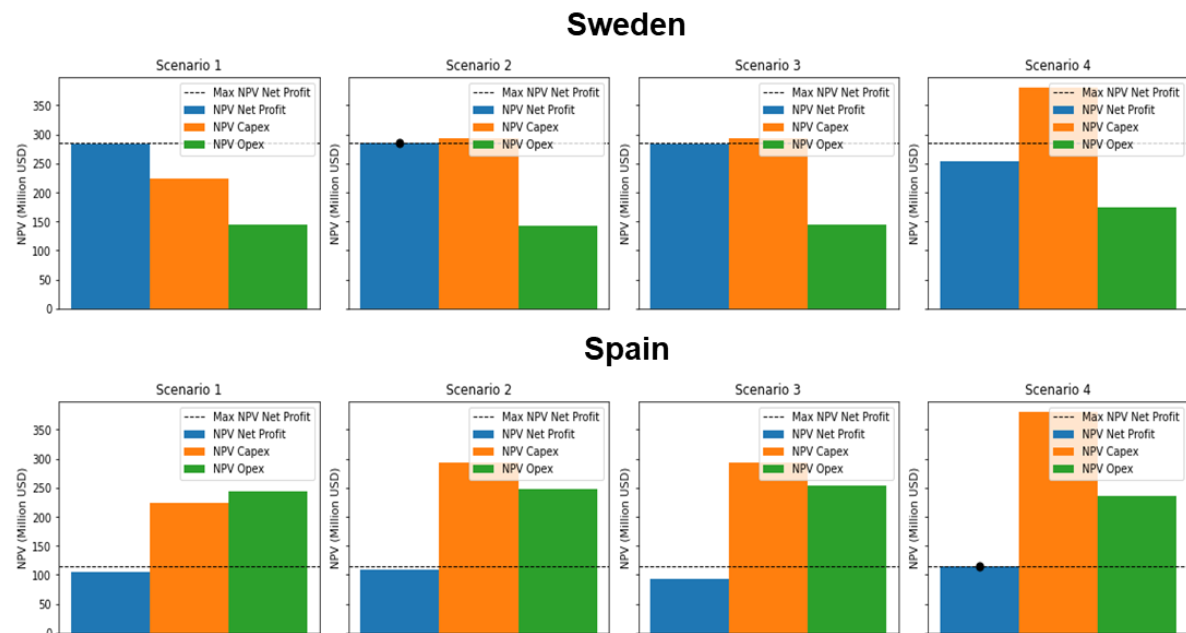


Figure 37. Economic KPIs for Sweden and Spain across scenario @120MWh - 3USD/kg

It is essential to emphasize that the bars representing OPEX and CAPEX do not account for any revenue generated, such as income from selling electricity to the grid. This income is reflected in the net profit figures. In simpler terms, CAPEX and OPEX solely incorporate negative values.

The optimal scenario isn't necessarily indicated by the highest net profit, as it could potentially result from elevated CAPEX and OPEX, thus increasing the overall project risk. In the case of Sweden, the most profitable scenario is Scenario 1, where only a PEM Electrolyzer is connected to the grid.

Conversely, for Spain, the scenario with the highest net profit is Scenario 4. However, it is crucial to note that the difference in profit compared to other scenarios is approximately 10%, while the difference in CAPEX is about 30% higher than Scenarios 2 and 3 and 70% higher than Scenario 1. Consequently, it can be inferred that despite generating greater profits, Scenario 4 does not represent the most economically viable choice.

Furthermore, it is worth highlighting that in the case of Spain, in Scenario 1, OPEX costs surpass CAPEX costs. In this particular scenario, where there is no option to store electricity during periods of low prices, the system is compelled to purchase electricity at higher rates, leading to increased operational expenses compared to capital expenditures. This circumstance is noteworthy within the context of this investment-intensive sector.

5.5 CO₂ Emissions

Figure 38 presents data on the CO₂ emissions per kilogram of H₂ produced within both scenarios 3 and 4, accounting for both countries. Scenarios 3 and 4 were selected due to their ability to evidence the impact of solar energy on this environmental metric.

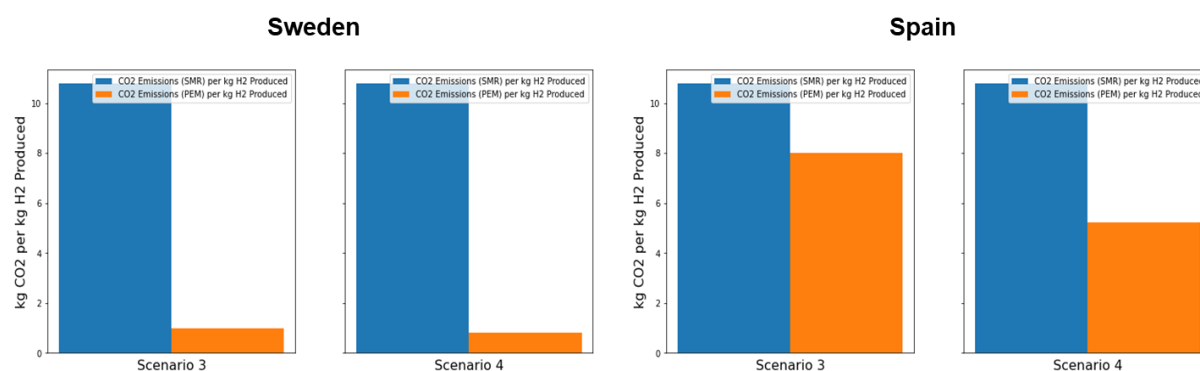


Figure 38. CO₂ emissions per kg H₂ produced in Scenario 3 (blue) and Scenario 4 (orange) for Sweden (left) and Spain (right)

In this analysis, the carbon contributions attributed to the solar farm are considered to be zero. While it is acknowledged that over the entire lifecycle analysis, solar farms do indeed have a carbon footprint, for the purposes of this dispatch-focused examination, the assumption is made that the solar farm is already in place. Consequently, when calculating the carbon footprint of hydrogen, a clear distinction must be made between electricity sourced from solar and that from the grid.

The total hydrogen production over the 20-year system lifetime, originating from solar energy, is determined by multiplying the fraction of energy from the solar farm (Solar_to_PEM) by the energy fraction from the Battery Energy Storage System (BESS_to_PEM) that can be attributed to solar energy (Solar_to_BESS). The remaining energy utilized in hydrogen production is assumed to be sourced from the grid, carrying with it the respective carbon footprint corresponding to the country in question. As previously established in the KPIs chapter, Sweden exhibits a carbon footprint of 1 kg of CO₂ per kg of H₂, while Spain records 8 kg of CO₂ per kg of H₂.

For the SMR benchmark, there is no differentiation based on whether hydrogen production is solar-assisted or not. Instead, it is directly assumed that all hydrogen production carries a uniform carbon footprint of 10.8 kg of CO₂ per kg of H₂.

The Swedish case reflects a substantial percentage reduction in carbon emissions, with Scenario 3 yielding a reduction of 90.74%, and Scenario 4 surpassing this with a reduction of 92.61%. Conversely, the Spanish case exhibits less pronounced reductions, with Scenario 3 achieving a reduction of 25.93%, and Scenario 4 demonstrating a more substantial reduction of 51.68%.

Furthermore, it is noteworthy to emphasize the minimal discrepancy between scenario 3 and 4 in the Swedish context, primarily attributed to its inherently clean electricity generation sources. Conversely, in Spain, the reduction in emissions between these scenarios is significantly more pronounced, nearing a 25-percentage-point difference.

6 Discussion

Figure 39 in (IEA, 2023) illustrates a global map with the Levelized Cost of Hydrogen (LCOH) across different regions. This map takes into account various factors such as the optimal combination of solar PV, onshore wind, electrolyzer, battery, and hydrogen storage capacities for each specific area.

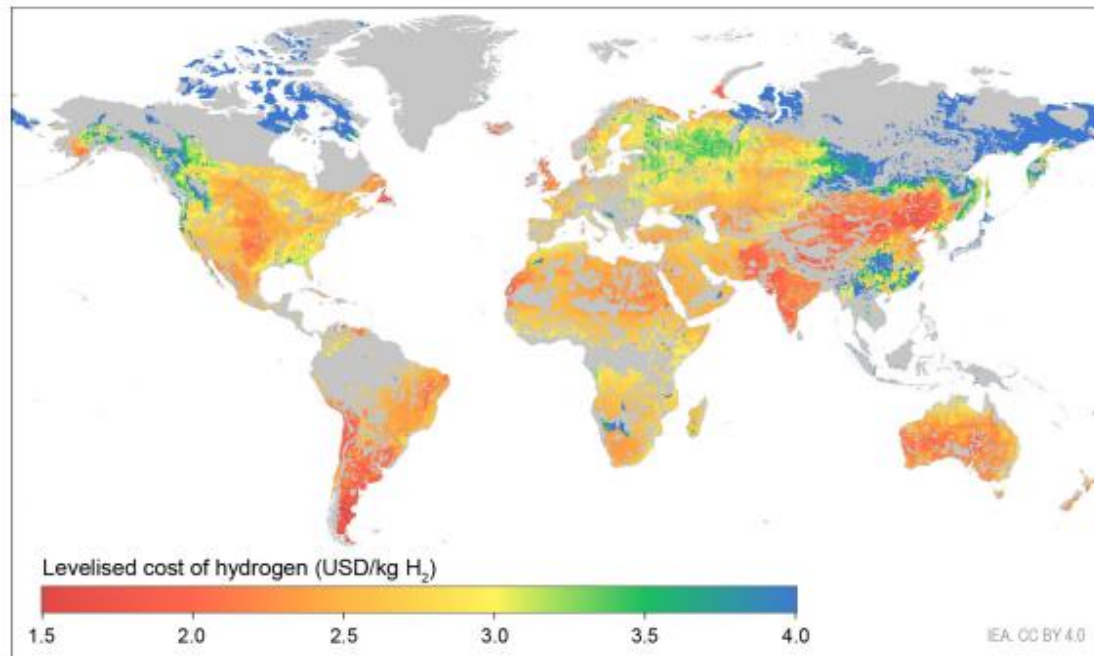


Figure 39. Levelized Cost of Hydrogen map using optimal multi-energy systems (IEA, 2023)

It is worth noting that the current research, in contrast, focuses exclusively on solar energy as the renewable source and does not factor in the associated expenses related to hydrogen storage. However, the outcomes align with the results of the sensitivity analysis conducted for hydrogen pricing. There are also differences in the methodology, particularly in the choice of the Weighted Average Cost of Capital (WACC), where this study employs a 6% rate compared to the 8% utilized in our investigation.

These discrepancies in the underlying frameworks prevent a direct comparison or validation of the findings between the two studies. Nevertheless, they do establish a basis for affirming that the results obtained in this research are within a reasonable range of values.

A notable finding from Figure 39 is the slightly lower Levelized Cost of Hydrogen (LCOH) observed in Spain when compared to Sweden. The reason may be attributed to the assumption made in the analysis, where it is assumed that 100% of the energy source is generated within the project itself, whereas this study considers projects connected to the grid. Consequently, it can be inferred that establishing a solar power facility in Spain to supply the

electrolyzer is potentially a more economically viable option than investing in a similar solar power plant in Sweden to serve the same electrolyzer.

On another note, evaluating extra revenue streams or storing capacity in these hydrogen-based projects may imply a larger CAPEX to manage the energy flows, however, they may reduce the risk of the projects if considering mature technologies. (Hydrogen Council, 2023) prepared a study about the stage at which the different hydrogen project being developed worldwide are in Figure 40.

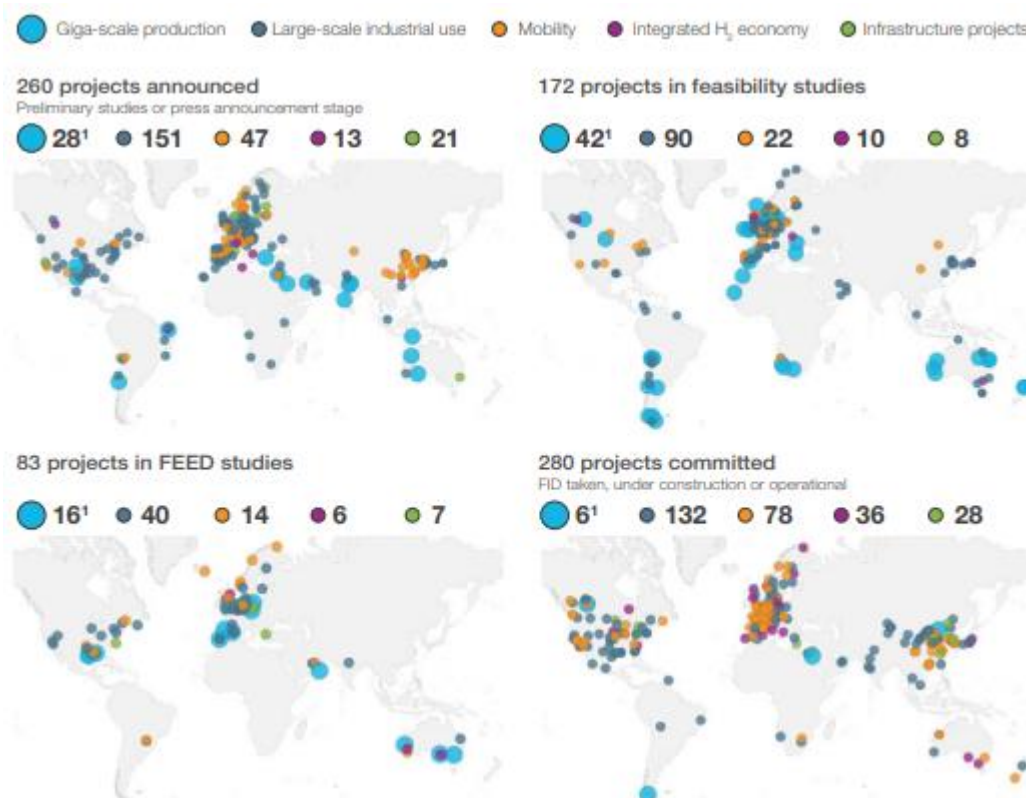


Figure 40. Development stage of hydrogen projects worldwide (Hydrogen Council, 2023)

The enhanced operation presented from multi-energy systems as the ones presented in this thesis could provide a relief during the feasibility study to alleviate the operational expenses (by increased revenue) and decreasing hydrogen production costs, by the trend of harnessing renewables and optimizing energy usage.

Interestingly, (Hydrogen Council, 2023) underscores that projects in their early stages typically necessitate an average investment of approximately USD 600 million. This figure underlines the increasing scale of hydrogen projects and closely aligns with the range of capital expenditure (CAPEX) costs identified in this study. Here, the investment costs range from roughly 224 million USD in Scenario 1 to 518 million USD in Scenario 4, which involves the largest BESS capacity.

Insights from (Bain & Company, 2022) provide valuable perspectives to secure long-term offtake agreements. The market for clean hydrogen is expanding rapidly, and it is evident that developers who establish a successful track record in clean hydrogen projects early on will be best positioned to thrive as the market matures in the 2030s. This aligns with the notion that multi-energy projects, such as those combining solar PV and electrolyzers, can yield high-value and profitable ventures in the emerging hydrogen economy.

The identification of customer segments willing to pay a premium for low-carbon hydrogen is essential, as securing long-term offtake agreements is often a determinant of project success. This resonates with the project location determined for both projects in this report and our finding that in countries with high electricity prices, performing price arbitrage by selling electricity back to the grid can generate more revenue than hydrogen production.

While the path to success in the clean hydrogen sector remains uncertain, (Bain & Company, 2022) underlines the importance of a customer-centric approach, emphasizing that it can be key in differentiating between project failure and success in the evolving hydrogen landscape. Developers who not only harness renewable energy sources but also align their strategies with customer needs and preferences will likely strengthen their position in this increasing market.

7 Conclusions and future work

In this analysis of multi-energy system configurations for hydrogen production, several insights have emerged, showing the complex dynamics of cost-efficiency and energy optimization. This study focused into the interplay of diverse energy sources, storage solutions, and grid integration strategies.

Within the context of the dispatch problem in a multi-energy system, employing a mathematical optimization method with a single objective proved to be a correct approach for problem-solving. It consistently delivered optimal solutions in each iteration, with a runtime of less than 1.5 min over the course of a year. The trade-off, however, was the necessity to introduce certain simplifications to linearize the system. Despite this, results remained aligned with the anticipated system behavior and found support in comparable findings from related research.

One of the central findings of this research is the limitations of conventional economic metrics such as Levelized Cost of Hydrogen (LCOH) in fully capturing the economic potential of multi-energy systems. While these metrics are fundamental for cost assessment, they do not fully capture the advantages of integrated systems. In the test 4, the net profit's NPV did not reflect the revenue from selling electricity into the grid, which in Spain was a major leverage when maximizing the hourly net profit.

Access to inexpensive electricity is a cornerstone in the development of electrolysis projects. This study demonstrates that the cost of electricity, whether derived from the grid or renewables, is a decisive driver in the viability of hydrogen production. Notably, the NPV of net profits in Sweden reached approximately 250 million USD, while in Spain, the equivalent metric was about 100 million USD.

Across the complete year, it was economically sound to generate hydrogen in Sweden due to its cheap electricity, whereas in Spain, during the winter months the algorithm was just meeting the daily hydrogen sufficiency. In the month of November, Swedish case produced approximately 1200kton, while the Spanish one produced around 300kton.

The investigation underscored the potential for profitable projects within the hydrogen economy through multi-energy systems. By integrating solar photovoltaics, energy storage, and grid interactions, these systems can be economically feasible for hydrogen production but also contribute to grid stability and energy security. Out of the 60 tests conducted, 21 resulted in a viable project when assessing only the LCOH. The most cost-efficient project had an LCOH of 1.38 USD/kg, while the least cost-efficient among the viable projects had an LCOH of 2.92 USD/kg.

Lastly, CO₂ emissions per kg of H₂ have proven to decrease in both countries when implementing a solution with PEM electrolyzer when compared to the

SMR alternative. The reduction amounts to around 90% for the Swedish scenario with a low carbon footprint and up to a 50% decrease for the Spanish case when solar energy is available.

Concerning future work, a notable area for improvement lies in the refinement of sizing algorithms. The current study employed a sensitivity analysis to explore different sizing configurations of system components. However, there remains significant room for improvement in understanding the interplay between these components. Future research could explore novel algorithms where dispatch optimization is conducted iteratively, allowing for adjustments in the sizing of various elements until an optimal configuration is reached. This approach may provide better economic KPIs while maintaining the essential dispatch behavior patterns established in this study.

To further enhance the model developed, future work should consider the inclusion of non-linear elements, such as the efficiency of the PEM electrolyzer, which can vary under different operating conditions. Additionally, considering factors like the non-linear degradation of energy storage systems or fuel cell stacks can provide a more accurate representation of real-world performance. Incorporating these non-linear elements into the models can help uncover subtle nuances and optimize system operation.

Expanding revenue streams is another promising avenue for future research since this study only considered as potential income sources hydrogen production and injecting electricity into the grid. For instance, investigating the feasibility of integrating the hydrogen production facility into flexibility markets. This approach would allow the system to adjust its output to align with the grid's dynamic needs, potentially enhancing the economic viability of multi-energy systems.

The future of multi-energy systems in the hydrogen landscape is promising and loaded with opportunities for further exploration. By refining sizing algorithms, incorporating non-linear elements, and diversifying revenue sources, researchers can continue to push the boundaries of knowledge in this field and contribute to the development of sustainable and economically viable energy solutions.

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